

AD-A128 796

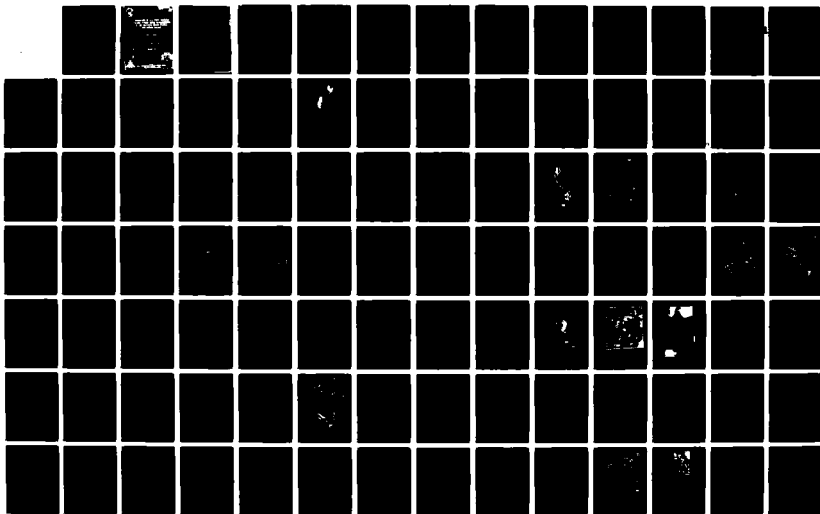
EVALUATION OF US NAVY TROPICAL CYCLONE STORM SURGE  
REQUIREMENTS IN THE WE. (U) SCIENCE APPLICATIONS INC  
MONTEREY CA A J COMPTON FEB 83 SAI-PN-1-425-02-423  
NEPRF-CR-83-02 N00228-81-C-H551

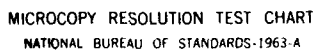
1/2

UNCLASSIFIED

F/G 15/3

NL





MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A



# EVALUATION OF U.S. NAVY TYPICAL CYCLONE STORM SURGE RECORDS IN THE WESTERN NORTH PACIFIC AND INDIAN OCEANS

Prepared by:

Andrew J. Compton  
Science Applications, Inc.  
Menlo Park, California 94025

Contract No. N00026-81-C-0391

March 1982

AD A128796

NO FILE COPY

QUALIFIED REQUESTORS MAY OBTAIN ADDITIONAL COPIES  
FROM THE DEFENSE TECHNICAL INFORMATION CENTER.  
ALL OTHERS SHOULD APPLY TO THE NATIONAL TECHNICAL  
INFORMATION SERVICE.

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE  |  | READ INSTRUCTIONS<br>BEFORE COMPLETING FORM |
|--|--|---|
| 1. REPORT NUMBER<br>NAVENVPREDRSCHFAC<br>Contractor Report CR 83-02  | 2. GOVT ACCESSION NO.<br><b>A128796</b>  | 3. RECIPIENT'S CATALOG NUMBER               |
| 4. TITLE (and Subtitle)<br>Evaluation of U.S. Navy Tropical Cyclone<br>Storm Surge Requirements in the Western<br>North Pacific and Indian Oceans  | 5. TYPE OF REPORT & PERIOD COVERED<br>Final  |   |
| 7. AUTHOR(s)<br>Andrew J. Compton  | 6. PERFORMING ORG. REPORT NUMBER<br>SAI PN 1-425-02-423  |   |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Science Applications, Inc.<br>205 Montecito Ave.<br>Monterey, CA 93940  | 8. CONTRACT OR GRANT NUMBER(s)<br>N00228-81-C-H551   |   |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>Naval Air Systems Command<br>Department of the Navy<br>Washington, DC 20361   | 10. PROGRAM ELEMENT, PROJECT, TASK<br>AREA & WORK UNIT NUMBERS<br>PE 62759N PN WF59-551<br>NEPRF WU 6.2-22 |   |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)<br>Naval Environmental Prediction Research Facility<br>Monterey, CA 93940  | 12. REPORT DATE<br>February 1983   |   |
|  | 13. NUMBER OF PAGES<br>138   |   |
|  | 15. SECURITY CLASS. (of this report)<br>UNCLASSIFIED   |   |
|  | 15a. DECLASSIFICATION/DOWNGRADING<br>SCHEDULE  |   |
| 16. DISTRIBUTION STATEMENT (of this Report)<br>Approved for public release; distribution unlimited   |  |   |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)   |  |   |
| 18. SUPPLEMENTARY NOTES  |  |   |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number)<br>Typhoons<br>Tropical cyclones<br>Tropical cyclone storm surge<br>Storm surge   |  |   |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number)<br>This document reports the results of a three-phased evaluation of the tropical cyclone storm surge threat to nine sites of U.S. Navy interest located in the western North Pacific and Indian Oceans: Inchon, Chinhae, Pusan, Yokosuka, Sasebo, Buckner Bay, Subic Bay, Guam, and Diego Garcia. A preliminary literature search was conducted to determine storm surges of record. Visits were made to eight of the nine locations to gather on-site data and conduct interviews. →<br>(continued on reverse) |  |   |

DD FORM 1473

1 JAN 73

EDITION OF 1 NOV 65 IS OBSOLETE  
S/N 0102-014-6601

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

→ The third phase consisted of an evaluation of collected data to determine sites with the greatest threat of storm surge, and the formulation of conclusions to aid the Navy in mitigating the threat.

|                    |  |         |
|--------------------|--|---------|
| Accession For      |  |         |
| NTIS GRA&I         | <input checked="checked" type="checkbox"/> |         |
| DTIC TAB           | <input type="checkbox"/>                   |         |
| Unannounced        | <input type="checkbox"/>                   |         |
| Justification      |  |         |
| By _____           |  |         |
| Distribution/      |  |         |
| Availability Codes |  |         |
| Dist               | Avail and/or                               | Special |
| A                  |  |         |



SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

## TABLE OF CONTENTS

|      |  |    |
|------|--|----|
| I.   | EXECUTIVE SUMMARY . . . . .                                      | 1  |
| II.  | STORM SURGE THREAT ASSESSMENT . . . . .                          | 3  |
|      | A. Background . . . . .  | 3  |
|      | B. Approach . . . . .  | 6  |
| III. | SITE STUDIES . . . . .   | 9  |
|      | <u>Guam</u> . . . . .  | 9  |
|      | A. References and Characteristics of<br>Available Data . . . . . | 9  |
|      | B. Physical Characteristics of Site . . . . .                    | 11 |
|      | C. Storm Surge Characteristics . . . . .                         | 15 |
|      | D. Summary . . . . .   | 25 |
|      | <u>Subic Bay</u> . . . . .                                       | 27 |
|      | A. References and Characteristics of<br>Available Data . . . . . | 27 |
|      | B. Physical Characteristics of Site . . . . .                    | 29 |
|      | C. Storm Surge Characteristics . . . . .                         | 34 |
|      | D. Summary . . . . .   | 40 |
|      | <u>Japan</u> . . . . .   | 43 |
|      | A. References and Characteristics of<br>Available Data . . . . . | 43 |
|      | Yokosuka   |    |
|      | B. Physical Characteristics of Site . . . . .                    | 46 |
|      | C. Storm Surge Characteristics . . . . .                         | 49 |
|      | D. Summary . . . . .   | 55 |
|      | Sasebo   |    |
|      | B. Physical Characteristics of Site . . . . .                    | 57 |
|      | C. Storm Surge Characteristics . . . . .                         | 61 |
|      | D. Summary . . . . .   | 65 |

TABLE OF CONTENTS  
(continued)

|  |            |
|--|------------|
| <b>Buckner Bay</b>   |            |
| B. Physical Characteristics of Site . . . . .                    | 67         |
| C. Storm Surge Characteristics . . . . .                         | 69         |
| D. Summary . . . . .   | 72         |
| <b><u>Diego Garcia</u></b>                                       |            |
| A. References and Characteristics of<br>Available Data . . . . . | 75         |
| B. Physical Characteristics of Site . . . . .                    | 76         |
| C. Storm Surge Characteristics . . . . .                         | 78         |
| D. Summary . . . . .   | 81         |
| <b><u>Korea</u></b>  |            |
| A. References and Characteristics of<br>Available Data . . . . . | 83         |
| <b>Inchon</b>  |            |
| B. Physical Characteristics of Site . . . . .                    | 86         |
| C. Storm Surge Characteristics . . . . .                         | 89         |
| D. Summary . . . . .   | 92         |
| <b>Pusan/Chinhae</b>   |            |
| B. Physical Characteristics of Site . . . . .                    | 94         |
| C. Storm Surge Characteristics . . . . .                         | 97         |
| D. Summary . . . . .   | 101        |
| <b>IV. ANALYSIS AND CONCLUSIONS . . . . .</b>                    | <b>103</b> |
| 1. Comments on Survey . . . . .                                  | 103        |
| 2. Analysis of Site and Storm<br>Characteristics . . . . .       | 108        |
| 3. Conclusions . . . . .   | 121        |
| <b>GENERAL REFERENCES . . . . .</b>                              | <b>123</b> |
| <b>APPENDIX A . . . . .</b>                                      | <b>A-1</b> |

## I. EXECUTIVE SUMMARY

The Naval Oceanography Command Center, Guam (NOCC Guam) has responsibility for tropical cyclone storm surge forecasting for Department of Defense activities in the western Pacific and Indian Ocean. A Navy Storm Surge Workshop was held in Monterey, California (March 1981), to discuss the needs of the Navy in forecasting tropical cyclone storm surge. It was noted that current Navy capabilities were limited, both in forecasting storm surge and in meeting requirements for long range planning. A two-staged plan was resolved which would address Navy needs. The initial stage would consist of a survey in the western North Pacific and Indian Oceans to clarify Navy needs at specified sites. The results of the survey would serve as a basis to formulate follow-on plans to meet the determined needs. This report constitutes the results of the initial survey.

A three-phased evaluation was conducted to determine storm surge threat at nine sites of U.S. Navy interest. The nine sites are: Inchon, Chinhae and Pusan in Korea; Yokosuka, Sasebo and Buckner Bay in Japan; Subic Bay, Philippines; Guam; and Diego Garcia. A preliminary literature search was conducted to determine storm surges of record at the nine sites. Eight of the nine sites (less Diego Garcia) were visited to gather on-site data from historical records and to interview U.S. Navy personnel and long-time local residents for memory of past storm surge events. The third phase consisted of an evaluation of site survey data and an analysis of past tropical cyclones which posed a threat to the individual sites.

Due to the low frequency of direct tropical cyclone strikes at most sites, the difficulty of accurate storm surge measurements, and the limited number of years of data in historical records, the literature search did not prove fruitful. Survey visits provided information and data of mixed value - some useful but not of sufficient quality or quantity to provide a useful data base. Analysis of past tropical cyclone parameters extracted from the National Climatic Center (NCC) Tropical Cyclone Tape (note Ref. 6) provided significant data<sup>1</sup> which, when combined with the site survey information, established a level of potential threat for each site. From this analysis Apra Harbor, Subic Bay, and Buckner Bay, emerged as high threat sites; Inchon Harbor and Diego Garcia as relatively low threat, and Yokosuka, Sasebo, Chinhae, and Pusan were evaluated as medium threat.

---

<sup>1</sup>National Climatic Center (NCC) Tropical Cyclone Tape - A source data tape from NCC Ashville, N.C. which provides historical data such as track, wind speeds, barometric pressure, etc. for past tropical cyclones by ocean basin.

## II. STORM SURGE THREAT ASSESSMENT

### A. Background

The U.S. Navy has an expressed need to develop tropical cyclone storm surge forecast guidance for the western Pacific and Indian Ocean areas. The annual threat to U.S. Naval assets and capability is high and requires constant vigilance, warning, and preparation during the tropical cyclone season. A concurrent need is statistically sound guidance in the areas of long range disaster planning and engineering design.

Current navy methods of forecasting tropical cyclone warnings do not include information on storm surge. The Naval Oceanography Command Center (NOCC) at Guam has the responsibility for tropical cyclone storm surge forecasting in the western Pacific and Indian Oceans. Useful storm surge information must be derived from a combination of historical statistical data and/or storm surge model output integrated with the tropical cyclone forecast. Although NOCC, through the Joint Typhoon Warning Center (JTWC), regularly forecasts tropical cyclones, there is limited<sup>1</sup> capability to utilize statistical data or storm surge models. In fact, a full statistical data base of the critical tropical cyclone parameters needed for the expressed

---

<sup>1</sup>A handbook "Storm Surge Forecasting" by J.W. Nickerson is the only tool currently available. It utilizes nomograms based on a "standard" tropical cyclone and a "standard" basin but was devised for western North Atlantic and Gulf of Mexico tropical cyclones and coastline/bottom topography. It extrapolates poorly to the western Pacific tropical cyclones or geophysical conditions.

sites of interest (Fig. 1) - Inchon, Chinhae, Pusan, Yokosuka, Sasebo, Buckner Bay, Guam, Subic Bay, and Diego Garcia - does not exist.

Current technology does exist to solve the storm surge forecasting problem. Two types of storm surge computer models are presently available. Open coast wall models are most efficient in use where the coastal bathymetry and topography are simple and regular in feature. The inundation model handles complex coastal geography more completely and deals with flooding of bays and estuaries and low inland areas. However, the application of either of these models to a specific area requires extensive data and modeling. Meteorological parameters of historical tropical cyclones are needed for the site to develop representative "storm" models to run the storm surge model and extensive bathymetric data (and topographic data for the inundation model) is required to develop an accurate model. Moreover, historical storm surge data is needed to check and tune the model. Therefore the development of a storm surge forecast capability is expensive and should be justified by demonstrated need. This may be difficult to document on a short historical time scale due to the nature of tropical cyclones.

As devastating as a major storm surge event can be, the long-term threat from a tropical cyclone-induced storm surge for any single habitation site is small. The first step in developing viable plans to reduce potential risk is to define the potential strike area and then to determine the probable tropical cyclone recurrence and severity for each area. This report discusses the results of a survey of

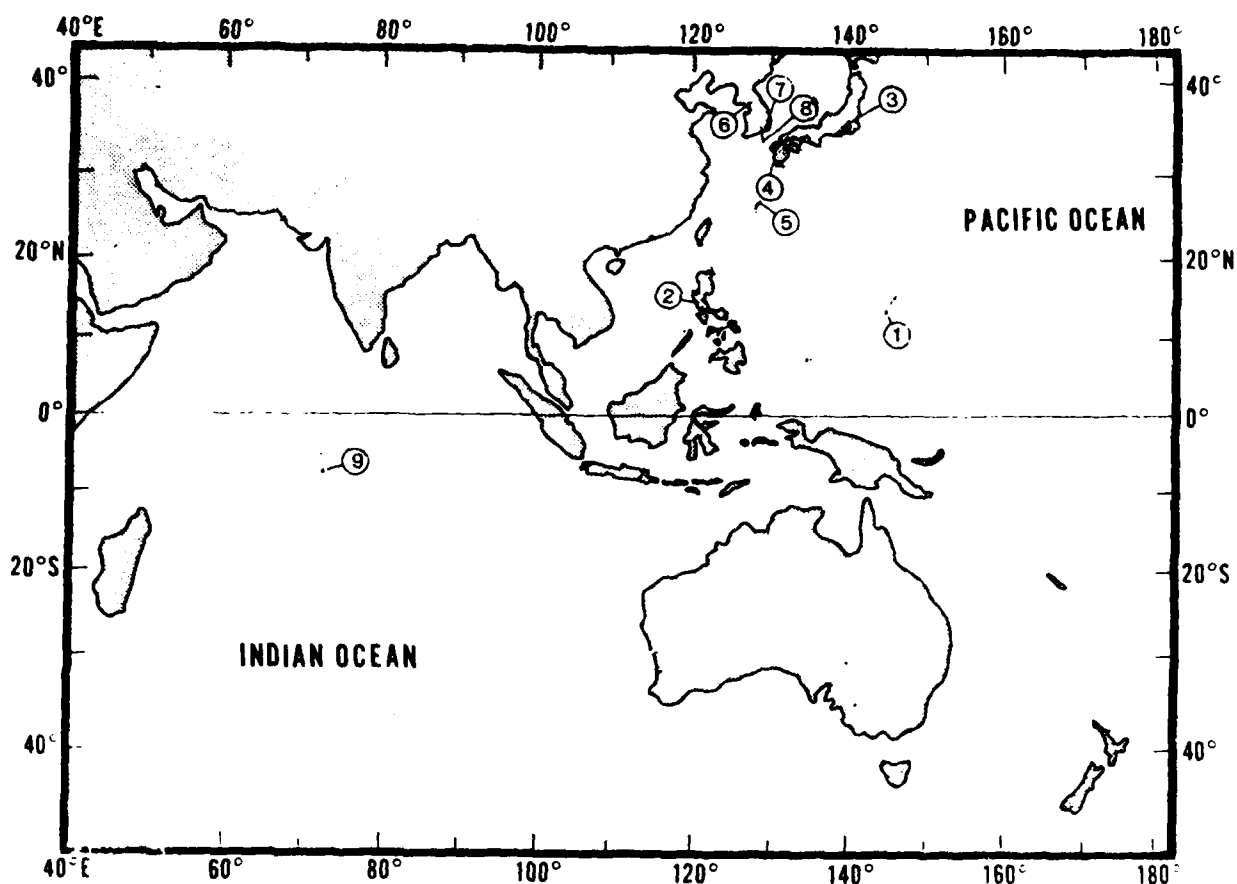


Figure 1  
U.S. NAVY STORM SURGE SITES OF INTEREST

1. Guam
2. Subic Bay, Philippines
3. Yokosuka, Japan
4. Sasebo, Japan
5. Buckner Bay, Okinawa
6. Inchon, Korea
7. Pusan, Korea
8. Chinhae, Korea
9. Diego Garcia

nine western Pacific and Indian Ocean sites and an analysis of the data to determine such information for each of the sites.

In some geographical areas storm surge and its associated dangers are well known due to a high frequency of occurrence and a significant level of past destruction. However, the danger from potential storm surge is greatly reduced in other areas due to the lower frequency of tropical cyclone occurrence and/or the complex geophysical setting of the location which in some cases serves to lessen the storm intensity or mitigate the actual surge. This complex geophysical configuration also leads to difficulty in assessing storm surge at a particular location.

#### B. Approach

A three-phased approach was planned to determine storm surge threat at the nine sites of U.S. Navy interest. First, a preliminary literature search was conducted to identify historical storm surges of record for each of the sites. Eight of the nine sites were visited to gather information from on-site personnel. The final phase consisted of evaluation of site survey data and analysis of past tropical cyclones which threatened the sites of interest.

A literature search was conducted in an attempt to locate site specific information. The local facilities/libraries of the U.S. Naval Postgraduate School and the Naval Environmental Prediction Research Facility were

visited as were two NOAA libraries in Rockville and Silver Spring, Maryland. A computer search on Lockheed's DIALOG system was also made, cross referencing site and subject titles. The U.S. Department of State, Agency for International Development (AID) disaster files were utilized to identify severe storms events at each site. Finally the National Climatic Center (NCC) Tropical Cyclone Tape was utilized to identify all tropical cyclones of record which approached within 180 nautical miles of each site and to provide meteorological and geographic data for those storms.

Visits were made to eight of the nine sites of interest. Preliminary telephone conversations with on-site personnel at Diego Garcia determined that there was no historical data available on storm surge and no one on the atoll who could provide information about past storm surge events. The primary purpose of the site visits was to identify and evaluate any local historical records (scientific, government, civil, educational, newspapers, etc.) which described, recorded, or evaluated past storm surge events. A point-of-contact was identified for each site (primarily U.S. Navy where available) and preliminary correspondence conducted to insure a coordinated visit.

A secondary purpose was to interview on-site personnel. Both U.S. Navy and native nationals were queried to obtain first hand information on past storm surge events. Professional government, civil authorities and scientists were interviewed where possible. Navy personnel were also queried in several other related areas of interest: high

water levels due to storm surge (or storm tide); evaluation of danger associated with tropical cyclones and methods of preparation for the storm; assessment of damage caused by storm surge; knowledge of storm surge and interest in storm surge forecast; etc.

The third phase of the approach consisted of an evaluation of the collected site survey data and an analysis of past tropical cyclones which threatened each site.

### III. SITE STUDIES

#### GUAM

##### A. References and Characterization of Available Data

###### 1. References:

- a. Pacific Islands Engineers, 1949: Report on General Survey of Damage to Navy Installations on Guam by Typhoon Allyn.
- b. Webb, R.M., J.T. O'Brien, and E.J. Beck, Jr., 1963: Study and Analysis of Damage by Typhoon Karen on Guam: Technical Note 497. U.S. Naval Civil Engineering Laboratory, Port Hueneme, California. 214 pp.
- c. CINCPAC, 1976: Super Typhoon Pamela - After Action Report, Guam CINCPAC REP GUAM/ TTPI.
- d. NOCC/JTWC Files, 1976: Typhoon Pamela Narrative.
- e. Holliday, Capt. Charles R., 1975: Tropical Cyclones Affecting Guam, FLEWEACEN Tech Note: JTWC 75-3, 75 pp.
- f. Marine Advisors, 1963: A Study of Average and Typhoon Wave Conditions at a Proposed Commercial Port, Apra Harbor, Guam, M.I., Prepared for Tudor Engineering Company by Marine Advisors, 30 pp.
- g. Mueser, Rutledge, Wentworth & Johnston; Consulting Engineers, 1968: Oceanographic Considerations, Preliminary Engineering Study for Graving Drydock, U.S. Ship Repair Facility, Guam, M.I., Mueser, Rutledge, Wentworth & Johnston; Consulting Engineers.
- h. 1982, Review of Newspaper Archives (Pacific Daily News, Guam Recorder) at Micronesian Area Research Center.

- i. Sea Engineering Services, Inc., 1980: Guam Comprehensive Study Shoreline Inventory.
  - j. Brown, M.E., and S. Brand, 1975: An Evaluation of Apra Harbor, Guam as a Typhoon Haven, NAVENVPREDRSCHFAC Technical Paper No. 1975.
  - k. Interviews with on-site U.S. Navy personnel including the following typical base units:
    - Naval Civil Engineering
    - Public Works Office
    - Ship Repair Facility
    - Port Operations
    - Naval Oceanography Command Center
    - Naval Oceanography Command Detachment
  - l. Interview with Director of Civil Defense Guam.
  - m. DMA Charts:
    - 81048, Island of Guam
    - 81054, Apra Harbor
2. Characterization of Available Data
- Available information on tropical cyclone effects upon the island of Guam was quite good compared to other sites visited. Damage reports and technical data on past tropical cyclones affecting Guam (Refs. a-e) were extensive and descriptive, although data was not in full agreement. Reference e was particularly comprehensive. Engineering studies (Refs. f and g) provided additional general oceanographic data on design storm waves, seiche and tsunami effects. A review of newspaper accounts provided only vague meteorological or oceanographic data (if any!) and dealt with

human interest stories - a poor source. Interviews with on-site personnel (as it did later at other sites) proved to be of limited value with a few exceptions. This was due primarily to limited on-site time and exposure to passing storms. Mr. Pete Robato (Guam Civil Defense Director) proved an exception to this with over 30 years of on-site storm memory.

A couple of observations follow which generally held true at each site. First - attempts to determine Navy needs for storm surge information proved quite difficult from an operational point of view. This is discussed in detail in Section IV - Analysis and Recommendations. Second - actual storm surge data (i.e., heights, duration and extent) varied from limited to none for the sites. Again, this is discussed in Section IV.

## B. Physical Characteristics of Site

### 1. Geographic Location (Figure 1)

Apra Harbor is located on the west side of the island of Guam at 13°26'N and 144°39'E. Guam is 5100 miles west of San Francisco and about 1500 miles east of the Philippines in the western North Pacific Ocean. It is the southernmost island in the Mariana Islands group.

### 2. Physical Description - Topography and Bathymetry (Figure G-1)

Guam is an island of volcanic origin 32 miles long with widths varying from 4 to 9 miles. A

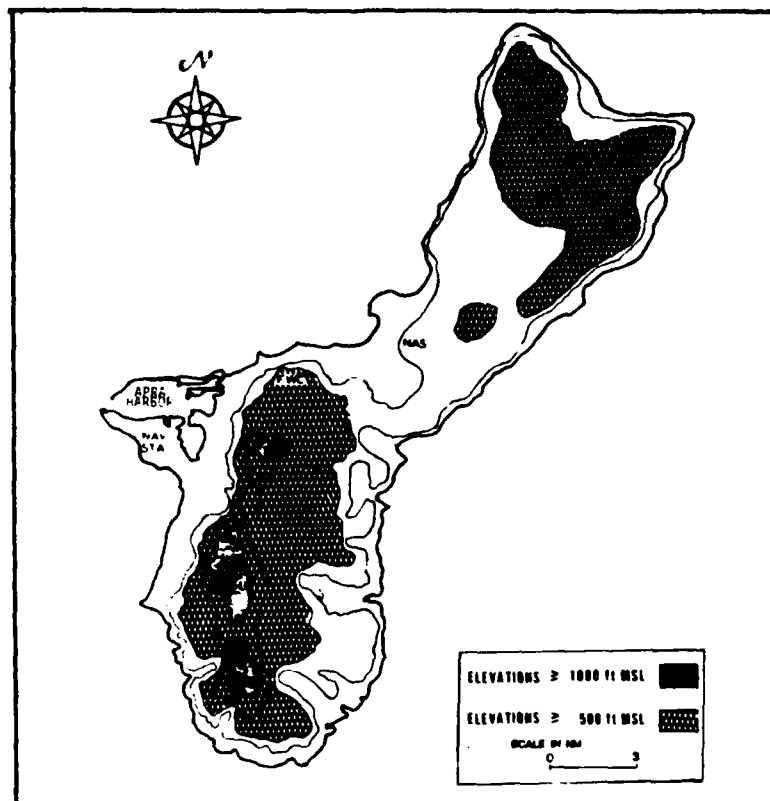


Figure G-1. Topography of Guam. Apra Harbor location (from Ref. 5).

fringing reef is present on all but the NE shoreline. Beyond the reef the depths increase rapidly to over one mile on all but the NE and SW octants where shoals are present. The island is sharply divided into a northern coral-line limestone plateau, which has an elevation of 500 ft, and a southern chain of low volcanic mountains. The mountains deeply eroded planes slope gently to the west and more steeply to coastal cliffs on the east.

Apra Harbor, which consists of an inner and an outer basin, is an improved natural harbor located on the southwest coast of the island. Orote Peninsula, which projects 4 n mi northwestward from the coast with heights to 200 feet, forms the southern boundary of the harbor. The northern boundary is a breakwater with an average height of 15 feet above mean sea level (MSL). The entrance is 500 yards wide, 100 feet deep and opens to the west. Average outer harbor depths range 100-150 feet with shoals at the eastern end. Inner harbor depths are 30-40 feet. Low hills (to 1000 feet) to the east of Apra Harbor provide some windbreak for easterly winds.

### 3. Location of Structural Development (Figure G-2)

The northern side of Apra Harbor (Cabras Island) is the location of the commercial port facilities for Guam. Orote Peninsula and the area around Inner Apra Harbor are sites for

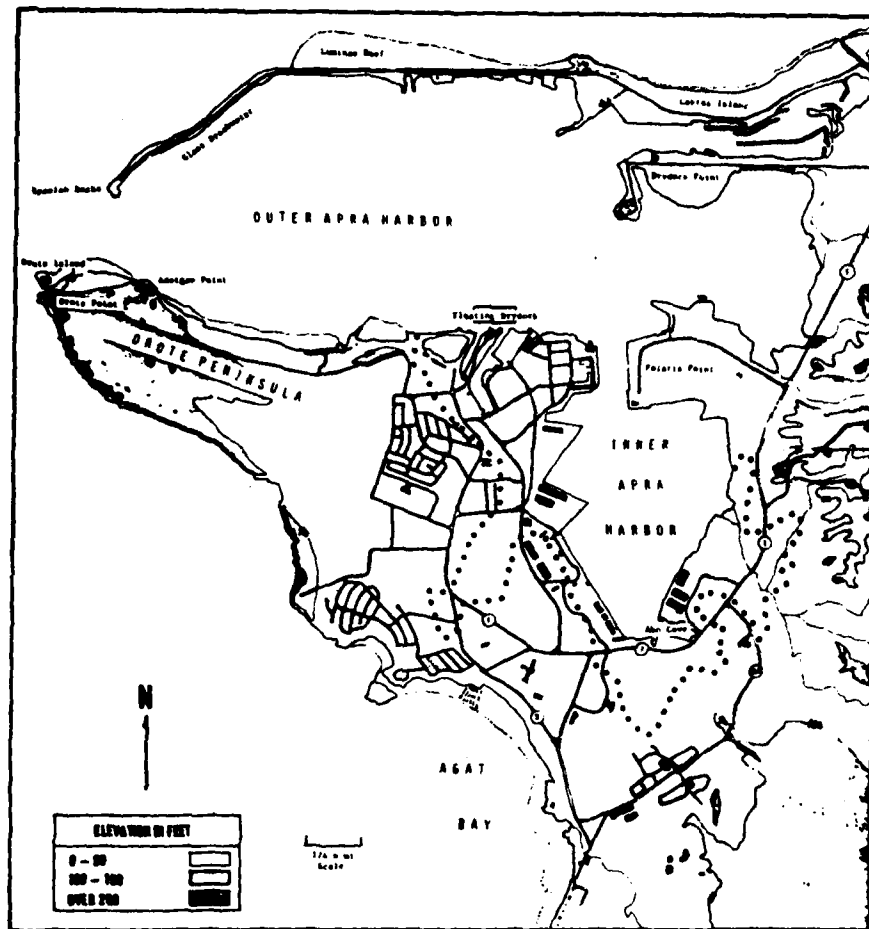


Figure G-2. Apra Harbor. Elevations and harbor development. Dotted line indicates 10 ft. elevation (from Ref. 5).

extensive U.S. Navy structures. Ground elevations range from 7-10 feet above MSL in most of the wharf and pier areas and slant gently up to foothills on the eastern side of the harbor. Orote Peninsula heights rise rapidly on the western end of the peninsula but low (<10 foot) elevations are found deep inland on the west side of the inner harbor and on the east side of both inner and outer harbor, creating a potential area for damage from heavy storm surge (note Fig. G-2).

### C. Storm Surge

#### 1. Tropical Cyclone Frequency and Characteristics

Guam at 13° north latitude, is in an area of active tropical cyclone generation and also lies along primary threat paths for storms generated to the east of the Mariana Islands. Guam may therefore be subjected to short notification due to rapid intensification of a developing storm or be threatened by a fully developed typhoon.

In an evaluation (Ref. 5 - note; numbered refs. are general refs.) of 27 years of data (1947-73), a total of 107 tropical cyclones were found to have passed within a 180 n mi radius of Guam. The 180 n mi radius was defined as a "threat" radius for passing tropical cyclones. The average yearly threat to Guam is thus about four tropical cyclones. An evaluation of the 35 year period from 1945 to 1979 (Ref. 6) determined that 46 of the 127 (36%) tropical cyclones had typhoon strength winds of 64 kt or greater while within the threat radius.

Evaluation of the direction of storm approach and passage (Refs. e, f, g, and j) determined that primary storm approach is from the east and southeast. Reference j gave 68% as the percentage of storms from those directions. It also determined primary storm passage to be north of the island (60%). However the occurrence of high winds on Guam was associated more with southern storm passage. This is probably due to the fact that the strong semicircle<sup>1</sup> passes over Guam during transits to the south.

Guam has been struck by several severe typhoons since 1946. Reference d states that 27 tropical cyclones have significantly affected Guam in the 30-year period 1946-75 with 13 producing typhoon force winds on the island. Four inflicted winds of over 100 knots. Due to heavy U.S. military presence since WWII and the fact that Guam is the site of both the U.S. Naval Oceanography Command Center and the Joint Typhoon Warning Center, the storms and their effects have been better documented here than most other sites. Typhoons Allyn (1949), Karen (1962) and Pamela (1976) caused extensive damage and storm effects have been well documented (note Refs. a, b, c, and d).

---

<sup>1</sup>The wind circulation associated with tropical cyclones is counterclockwise about the eye in the Northern Hemisphere with the more intense winds located in the right (facing direction of movement) semicircle of the storm. Hence the right side is known as the dangerous or strong semicircle.

Typhoon Allyn moving at 12 kt WNW passed 60 n mi south of Guam and, with center winds of 135 kt, caused sustained winds close to 100 kt on Guam and gusts well over 100 kt. Allyn caused high winds (>34 kt) for more than 37 hours (Ref. e). Typhoon Karen (Nov. 1962) is believed to be the most intense storm to strike Guam since the Nov. 1900 storm. Central pressure measured at NAS Agana was 931.9 mb and estimated (anemometer failed at 125 kt) highest winds were 173 kt sustained and over 200 kt<sup>2</sup> in gusts (Ref. b). Central pressure for the storm was estimated at 912 mb (Ref. e) and a measurement at Naval Magazine was actually below that at 907.6 mb. Karen passed over the southern part of the island moving westward at 17 kt.

Typhoon Pamela, also referred to as "Super Typhoon Pamela" (a popular designation for typhoons with center winds of 130 kt or more), was actually somewhat weaker than Karen as highest winds were estimated to be 20-25 kt less than Karen's (anemometer broke at 138 kt). Pamela with only 7 kt forward motion allowed the storm to cause great destruction. (Winds in excess of 100 kt were observed for 6 hours; typhoon force winds for 18 hours and winds in excess of 50 kt for 30 hours.) Pamela crossed

---

<sup>2</sup>Reference e estimated highest winds of 130 kt with 150-160 kts for gusts.

Guam on a path just north of that of Karen's and continued to maintain 120 kt intensity for 36 hours after passage. Much of Pamela's damage was from extensive rainfall (27 inches in 24 hours).

## 2. Characteristics of Storm Surge

Examination of storm surge characteristics can be divided into three problem areas: (1) surge on the open coast; (2) hydraulic flow of water of the surge on the open coast through inlets and over barrier islands into the bays and estuaries; and (3) wind set-up within the bays. Open coast storm surge on Guam is mitigated to a great degree due to the steep sloped volcanic nature of the island. Yet surge does occur at enclosed bays around the island and along coastal roads. Holliday (Ref. e) feels that significant inundation should be expected in low lying coastal areas with the passage of a tropical cyclone of typhoon strength within 60 n mi of the island. However, as Holliday indicates: "Specific information on Guam storm surges is quite sketchy as little reliable documentation as to their extent and height are available." (Holliday's Tech Note contains good historical documentation of past storms.)

Guam, of those sites studied, has been subjected to the most severe typhoons. The severity of the storms, and the propensity of man to utilize natural harbors along coastal areas, increases the potential danger from surge. Although Guam does not have any large

natural harbors on the east coast (the more dangerous side for typhoons approaching the island), both Agana and Apra harbor on the west coast have suffered severe inundation (Refs. b, e-h, k and l). The severe 1900 storm and typhoon Karen (1962) both forced water up to the Plaza of the Palace in Agana (Refs. e and l) - a height of approximately 12 feet above mean sea level (MSL). The city of Agana lies in a low (<10 feet above MSL) swampy indentation on the west coast. Coastal road heights are about 7-9 feet above MSL and do not form an effective barrier for severe storm water levels. During Karen, storm surge and wind/wave action washed boats weighing several tons up onto Marine Drive and other debris several blocks inland.

Apra Harbor has also suffered inundation up to 10-12 feet above mean lower low water (MLLW). Webb, et al (Ref. b) discusses in detail the damage caused and gives hindcast data on characteristics of Karen. The tidal gauge in outer Apra Harbor was inoperative for Karen and failed during Pamela. (Note - actual measurements of surge, swell, wind wave heights and other characteristics are almost universally missing for severe storm events.) Survey work (Ref.b) conducted after passage of Karen indicated that the highest water levels were at Ritidian Point, at the north end of the island, which experienced 20 foot plus levels (above MLLW). The eastern side of the island experienced levels of plus 12 to 16 foot MLLW.

Isolated surges of plus 20 to 30 foot MLLW occurred in the flatter coastal areas where the north boundary of the wall cloud of the typhoon made land strike. The inner basin of Apra Harbor with 12 foot plus MLLW appeared to be one of the areas of least surge.

Mr. Robato (Ref. 1) indicated that the worst storms to affect the Apra Harbor area were the Nov. 1900, Nov. 1940, and the Aug. 1941 storms before construction of the Glass Breakwater; and Typhoon Karen after installation of the breakwater. In all cases high water flooded the lower land areas and wave action (more severe before the breakwater was installed) was a contributive factor.

Reference g, an engineering study for a graving drydock in the outer harbor, considered all types of wave statistics and their interactions within Apra Harbor. A short summary of the report is important in that it ties together all those elements contributing to high sea levels within the harbor. Typhoon generated sea within the harbor riding on storm surge was determined to be the major causative factor for high water; however, all of the following were considered:

- o Tsunami
- o Typhoon waves generated outside/inside Apra Harbor
- o Normal sea and swell outside (sea inside) the harbor

- o Seiching
- o Astronomical tides
- o Meteorological tides (storm surge)
- o Wind set-up

Tsunami, seiche and normal sea and swell were all negligible components of high water levels. Tsunami have been recorded in Apra Harbor with a maximum wave height of 1.3 feet. Six major tsunami disturbances were recorded in the harbor over a 13-year period (1952-1964); all causing less than a one-foot rise in sea level. There are three primary seiche modes in the harbor, but they are felt to be insignificant as they are poorly tuned or too little energy is available.

Typhoon waves generated outside Apra Harbor are compared to those generated within the harbor in the Table G-1. Outside waves assume 40 n mi deepwater fetch from the NW. It is significant to note from the tables that typhoon waves from outside Apra Harbor are reduced by entrance into the harbor and are insignificant compared to waves generated within the harbor as contributors to total water height. (Two other sources, Refs. b and f, gave maximum in-harbor generated waves on the order of 7-9 feet for Karen. This differs from the calculated tables, just presented, [Ref. g].)

Astronomical tide, storm surge and wind set-up generate the water elevation upon which the waves will ride. The sea level datum for Guam

Table G-1

A comparison of tropical cyclone waves generated outside Apra Harbor with those generated within Apra Harbor. A 40 n mi deepwater fetch from the NW was used for the waves generated outside the harbor (from Ref.g).

TROPICAL CYCLONE WAVES GENERATED OUTSIDE APRA HARBOR

|                    |     |      |      |      |       |       |
|--------------------|-----|------|------|------|-------|-------|
| Wind Speed<br>(kt) | 50  | 75   | 100  | 125  | 150   | 200   |
| Hs (ft) ocean      | 15  | 23   | 33   | 45   | 55    | 70    |
| Hs(ft) at site     | 3.0 | 3.0  | 4.3  | 5.8  | 7.7   | 14.0  |
| P                  | 0.4 | 0.09 | 0.03 | 0.01 | 0.006 | 0.002 |

TROPICAL CYCLONE WAVES GENERATED WITHIN HARBOR

|        |       |       |       |      |      |      |
|--------|-------|-------|-------|------|------|------|
| Hs(ft) | 28    | 26    | 24    | 20   | 14   | 9    |
| P      | 0.001 | 0.004 | 0.007 | 0.02 | 0.04 | 0.15 |

- P = Probability of height condition being exceeded in a given year
- Hs = Significant wave height during storm associated with probability P.
- Site = Comparison site within the harbor is at drydock site near the entrance to the inner harbor basin with a north-south fetch.

is Mean Lower Low Water (MLLW). Mean tide level is 1.4 feet above MLLW, mean high water is 2.3 feet and predicted maximum tidal range is 3.5 feet above MLLW. Inverse barometric pressure rise was calculated at 3.3 feet for a typhoon Karen storm (907.6 mb central pressure). Wind set-up was calculated at one foot or less. The combined effects for a maximum still water level (e.g., a reference level for wave action) is presented in Table G-2 (from Ref. g).

Table G-2  
Calculated maximum still water levels for Apra Harbor (Ref. g) for winds from NW.

|                                   | AVERAGE WIND SPEED IN KNOTS |     |     |     |     |    |
|-----------------------------------|-----------------------------|-----|-----|-----|-----|----|
|                                   | 200                         | 150 | 125 | 100 | 75  | 5  |
| Reference Level<br>in Ft. on MLLW | 6.4                         | 5.0 | 4.3 | 3.6 | 3.0 | 2. |

The conclusions reached in the study (Ref. g) were as follows<sup>3</sup> (not a complete list):

- o Locally generated typhoon sea within Apra Harbor caused greatest impact.
- o There is a probability of about 0.001 that a combination of astronomical tide,

<sup>3</sup>Note - Results of engineering studies in general yielded different results for the same site. Since most of the evaluating techniques were similar it must be assumed that the statistical data bases used to calculate the data must have varied widely.

meteorological tide (surge) and wind set-up will raise the general sea (still water) in Apra harbor to +6 ft MLLW. Normally a rise in sea level to +3 ft MLLW can be expected with a passing typhoon.

- o Extreme typhoon conditions as indicated by typhoon Karen caused a run-up<sup>4</sup> of +12 ft MLLW.

---

<sup>4</sup>Damage reports (Ref. b) indicated a high water mark of 12 feet above MLLW. It is probable that the run-up was due to a combination of hydraulic forcing of water into the enclosed harbor area and waves riding on the elevated water level.

#### D. Summary

##### 1. Area Impact

Guam has suffered severe storm surge as indicated in references a-h, k and l. Reference e in particular summarizes past storm effects upon Guam. The storms which caused significant surge upon Guam are documented from 1946 to 1975 but data is primarily based upon narrative reports. Inarajan and Talofofo Bays (SE coast) suffered inundation during typhoons Allyn (1949), Lola (1957) and Karen (1962). Merizo (S coast) reported water 4-5 feet high during Lola (1957) and Cocos Island was completely inundated by Allyn (1949). On the western coast Agat suffered severe damage during the September 1946 storm and Karen (1962), while Agana was inundated at least twice - once by the 1900 (November) storm and by Karen (1962).

##### 2. Apra Harbor

Major inundations in the Apra Harbor region occurred at least five times during this century. The 1900 (November), 1940 (November), 1941 (August), 1962 (Karen) and 1979 (Pamela) storms all created high water and major damage in the Apra Harbor area. The two most recent events, Karen and Pamela, were estimated to have caused total damages of \$250 and \$200 million, respectively on Guam. Typhoon Karen was particularly damaging to the Apra Harbor area (Ref.b) and craft and structures within the harbor. Typhoon Pamela's total damage to the U.S. Navy property alone was \$120 million. (An attempt by this researcher to determine those damages due to storm surge alone or surge aided damage proved impossible. Damage reports primarily addressed cost replacement and not cause.)

### 3. Evaluation

Guam lies on a primary tropical cyclone threat path and, of the sites studied, has been struck by more powerful typhoons. The major population center of Agana and the U.S. Navy complex at Apra Harbor have considerable facilities located upon low-lying ground (<10 ft elevation above MLLW). These areas have been subjected to seven major inundations with resultant major damage since 1900. The frequency of typhoons and the vulnerability of the above sites to storm surge suggests that Guam is a prime choice for a storm surge modeling effort.

### III. SITE STUDIES

#### SUBIC BAY

##### A. References and Characterization of Available Data

###### 1. References:

- a. Arafiles, C.P. and C.P. Alcances, Jr., 1978: Typhoon Research Project - Storm Surges, Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), 96 pp.
- b. Asuncion, J.F., E.M. Parong, and A.S. Santos, 1979: Tropical Cyclones in the Philippine Areas of Responsibility 1948-1977 (30 years), PAGASA, 80 pp.
- c. Kintanar, R.L., L.A. Amadore, and R.P. Lao, 1979: Tropical Cyclone Hazard in the Philippines, PAGASA, 44 pp.
- d. Local Study (Source Unknown), Case Study Report on Typhoons Winnie (June, 1964) and Irma (May, 1966), nd, np.
- e. Arafiles, C.P., 1982: Personal letter and Storm Surge Model Run on Subic Bay Entrance.
- f. Douglas, J.A., 1975: An Evaluation of the Harbors of Subic Bay and Manila, Republic of the Philippines, as Typhoon Havens, ENVPREDRSCHFAC Tech Paper No. 13-75.
- g. Brand, S. and J.W. Blelloch, 1972: Changes in the Characteristics of Typhoons Crossing the Philippines, ENVPREDRSCHFAC Tech Paper No. 6-72.

- h. Interviews with on-site U.S. Navy personnel and Philippine employees including the following typical base units;
  - Naval Civil Engineering
  - Public Works Office
  - Port Operations
  - Naval Oceanography Command Detachment
- i. Interviews with individuals within the following Philippine offices at Manila and Quezon City:
  - Philippine Atmospheric, Geophysical and Astronomical Services (PAGASA)
  - Bureau of Public Works - Ports and Harbors
  - Bureau of Coast and Geodetic Survey
- j. Johnson, J.W. and R.L. Wiegel, 1955: Waves at Subic Bay, Philippine Islands, Cont. No. 479349, Bureau of Yards and Docks, Dept. of Navy.
- k. DMA Charts - No. 91289 Subic Bay
  - No. 91286 Port OlongapoPWC Survey Chart Subic Bay

2. Characteristics of Available Data

The Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) has actively pursued typhoon research and mitigation in the Philippines. References a,b and c are some of the results of that effort and provide a good historical data base as well as an attempt to predict storm surge (Ref. a). Actual data for the Subic Bay area was,

however, very limited. Reference d provided actual ship reports from several points in the harbor during two typhoons.

The interviews with on-site personnel provided some information on storms of recent history but no measured or recorded data on storm surge. (There is no tidal gage in Subic Bay.) Analysis of wind data (Ref. f) over a 19 year period provided a limited data base and analysis of storm intensity over that period. Subic Bay, as in other areas where major damage has not occurred in recent history, does not have much available storm surge data on record.

## B. Physical Characteristics of Site

### 1. Geographic Location (Figure SB-1)

Subic Bay is located at 14°48'N, 120°14'E on the west coast of Luzon, the largest of the Philippine Islands. The Philippines constitute the largest island group of the Malay Archipelago which lies in the western North Pacific Ocean. Subic Bay is approximately 50 mi WNW of Manila on the western side of the Bataan Peninsula.

### 2. Physical Description - Topography and Bathymetry

Figure SB-2 depicts the topography and bottom contours of the Subic Bay area. The land form surrounding the bay is very hilly with heights 1000-2000 ft in all quadrants except the south-southwest. These hills provide some protection

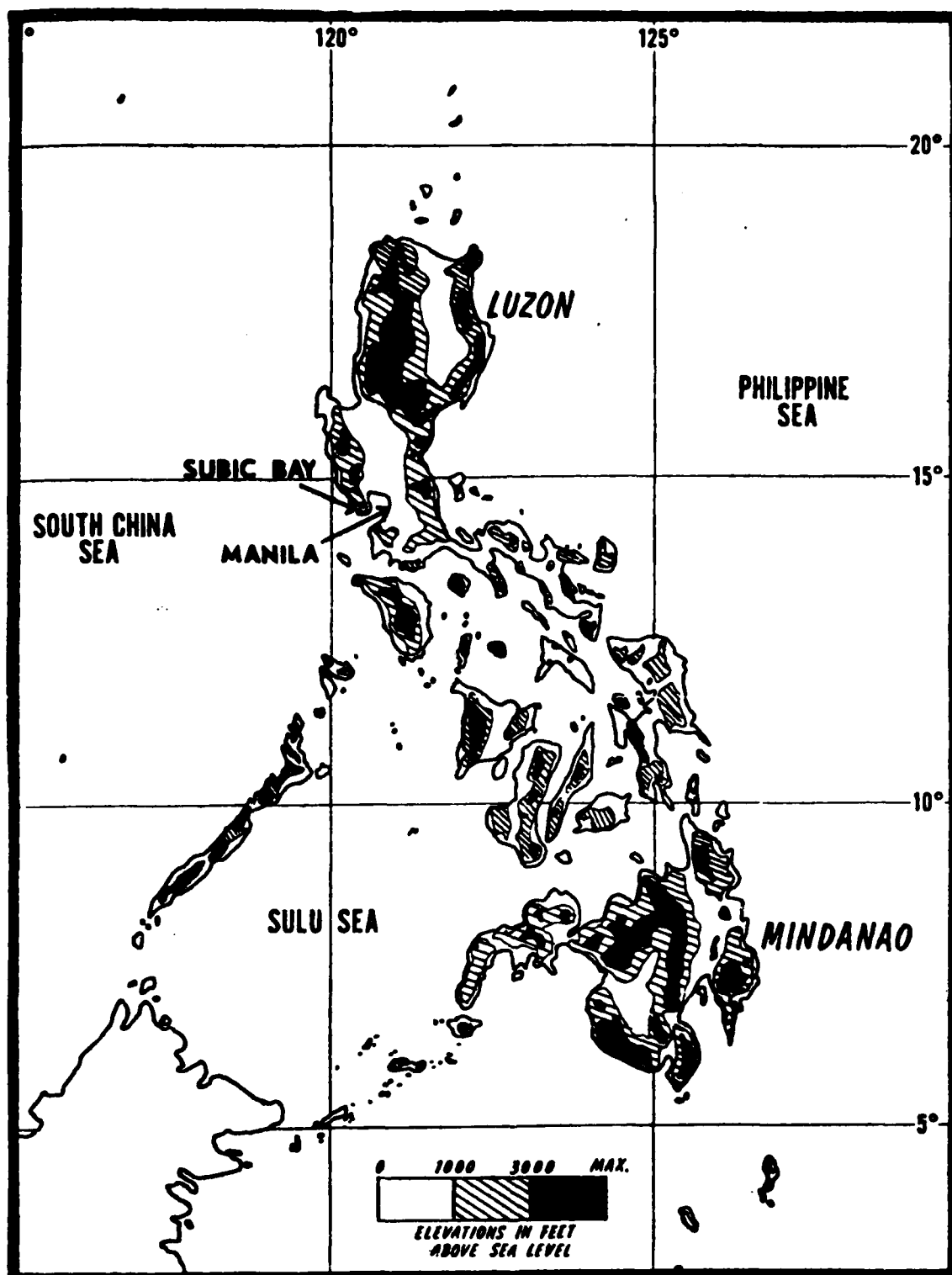


Figure SB-1  
Philippines topography map. Subic Bay location  
(from Ref. f).

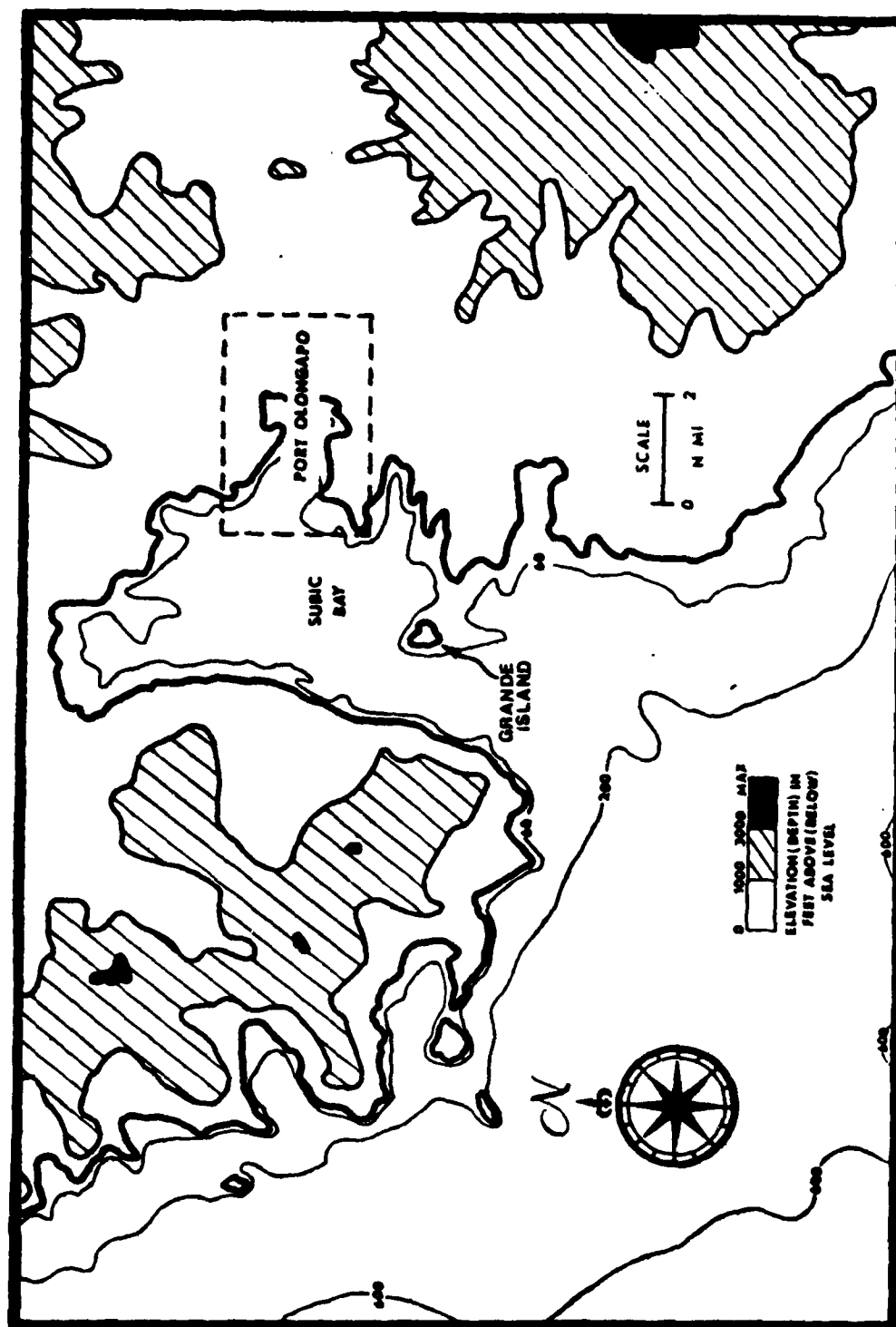


Figure SB-2.  
Subic Bay. Topography and bathymetry. Elevations and depths in ft (from Ref.f).

as a wind barrier for areas of the harbor (Ref. 7). The degree of protection is highly dependent upon wind direction and point of measurement within the harbor. Peaks in excess of 4000 feet lie to the northeast and southeast, with passes through the mountains to east-northeast and to the northwest of the bay. The net effect of the mountainous terrain is to dissipate typhoon energy for the normal east to west path across the Philippines.

Subic Bay (Fig. SB-2) is about 10 miles long, 5 miles wide and opens seaward to the southwest. Navy Port Olongapo (Fig. SB-3), in the northeast corner of the bay, consists of an Outer Harbor and an Inner Basin. U.S. Naval Air Station at Cubi Point is located on the southern side of the Outer Harbor. Depths in Subic Bay decrease regularly from about 180 feet in the entrance to about 50 feet near its head. The greater part of the bay has been swept to a depth of 49 feet. The entrance at Subic Bay is about 2600 yards wide between Grande Island (west side) and Macmany Point. Depths outside the harbor entrance fall gradually away to a depth of 600 feet at about 5 miles from the entrance.

3. Location of Structural Development (Figure SB-3)

U.S. Navy development in Subic Bay lies primarily around Port Olongapo from Kalaklan Point to Cubi Point. U.S. Naval Station, Ship Repair

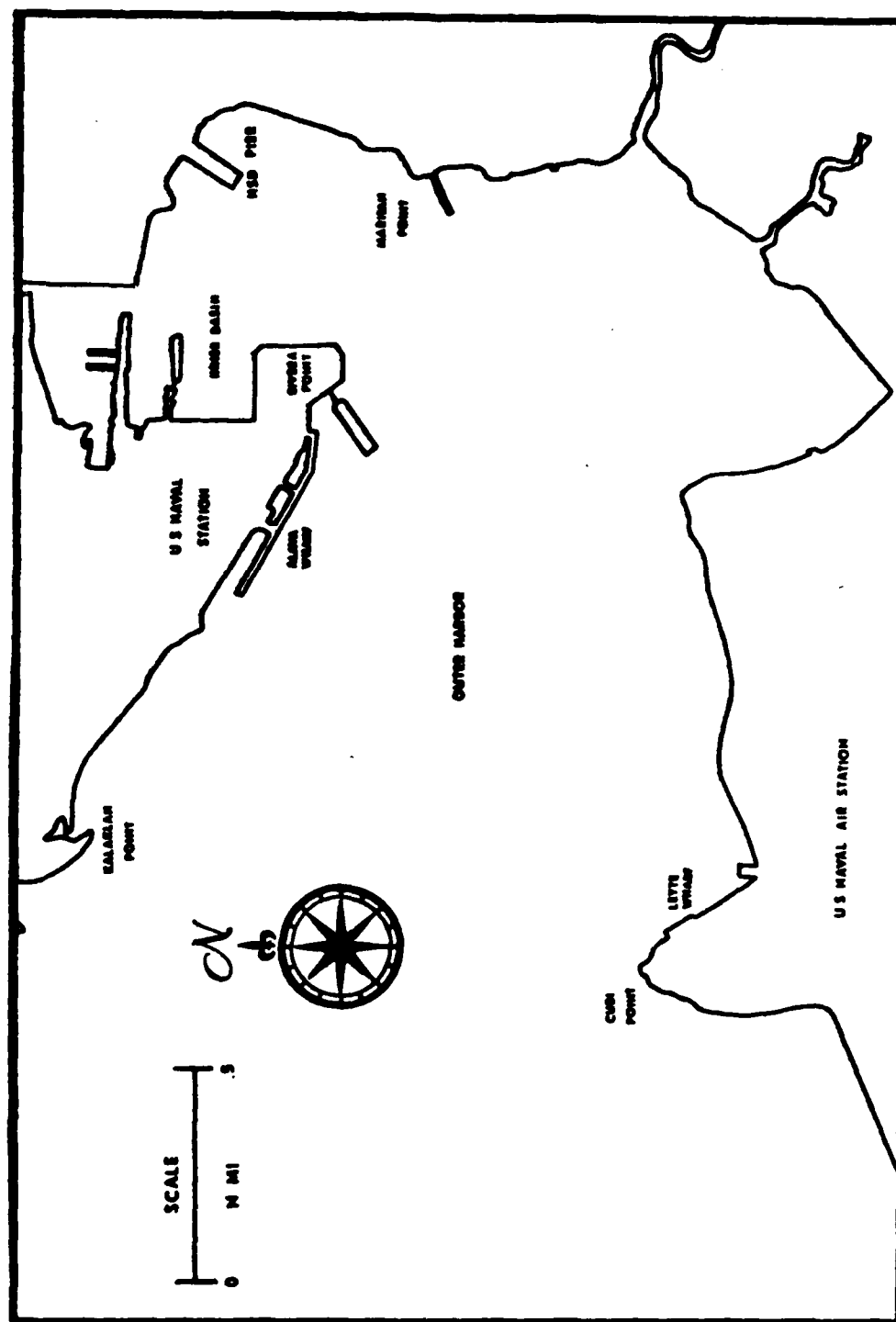


Figure SB-3.  
Port Olongapo. Location of structural features and sites (from Ref. f).

Facility, Port Operations, Public Works, Alava Wharf and Marine Terminal Pier lie on the north side of the port. The Subic Power Plant, POL Fuel Pier and POL storage areas lie on the east side of the port while the Cubi Point Naval Air Station and support facilities reside on the south shore of the Port Outer Harbor along with Leyte Wharf. The area on the north side of the port, which is exposed to longer overwater wind fetch, is also of lowest elevation (7-9 ft above MSL) in the port area. The ground to the east, also of low (10-12 ft MSL) elevation, is subject to innundation during severe surge. The south side of the port is of generally greater elevation.

C. Storm Surge

1. Typhoon Frequency and Characteristics

At 15°N latitude Subic Bay lies along primary threat paths for tropical cyclones for the majority of the tropical cyclone season (Ref. 10). Asuncion et al determined (Ref. b) the average annual frequency of tropical cyclones which cross the Philippines to be about 8 1/2 per year of which approximately one-half (123 of 258 for 30 year period 1948-1977) were of typhoon strength. Douglas (Ref. f) evaluated 19 years of data (1955-1973) and determined that a total 83 tropical cyclones passed within 180 n mi of a point midway between Subic Bay and Manila Bay. Analysis of data of a similar radius around Subic Bay over a 35 year period (1945-1979) from the NCC Tropical Cyclone Tape

(Ref.6) provided 160 threat cyclones (about 4.5 storms per year); 72 storms (48%) had winds of typhoon strength while within the threat radius.

Kintanar et al. (Ref. c) provides some interesting data on the characteristics of tropical cyclones affecting the Philippines. Figure SB-4, (Ref. c) depicts an analysis of typhoons by intensity (in kt) for each 1° longitude, latitude square from 1950-1978. The figure seems to show a great loss of storm intensity in passage over the mountainous terrain of the Philippine Islands. (Not totally conclusive as recurvature of storms occurs along east coast also.) This is further supported in research by Brand and Blelloch (Ref g) which demonstrated a large decrease in typhoon intensity for strong (>90 kt) typhoons crossing the Philippines.

The direction of approach for tropical cyclones threatening Subic Bay is primarily from the eastern quadrant - 70% of the 83 storms during the 1955-1973 period (Ref. f). Sixty percent of the storms passed north of the bay and 40% south, and only 13% of the 83 storms resulted in gale force or higher winds at Subic Bay. (Measured at Cubi Point - actual winds over Subic Bay may be 3-5 kt higher). 56 kt was the highest reported sustained wind for the period (Ref. f). Typhoon Irma (Nov, 1974) passed 30 n mi north of Subic with center winds of 70-75 kt

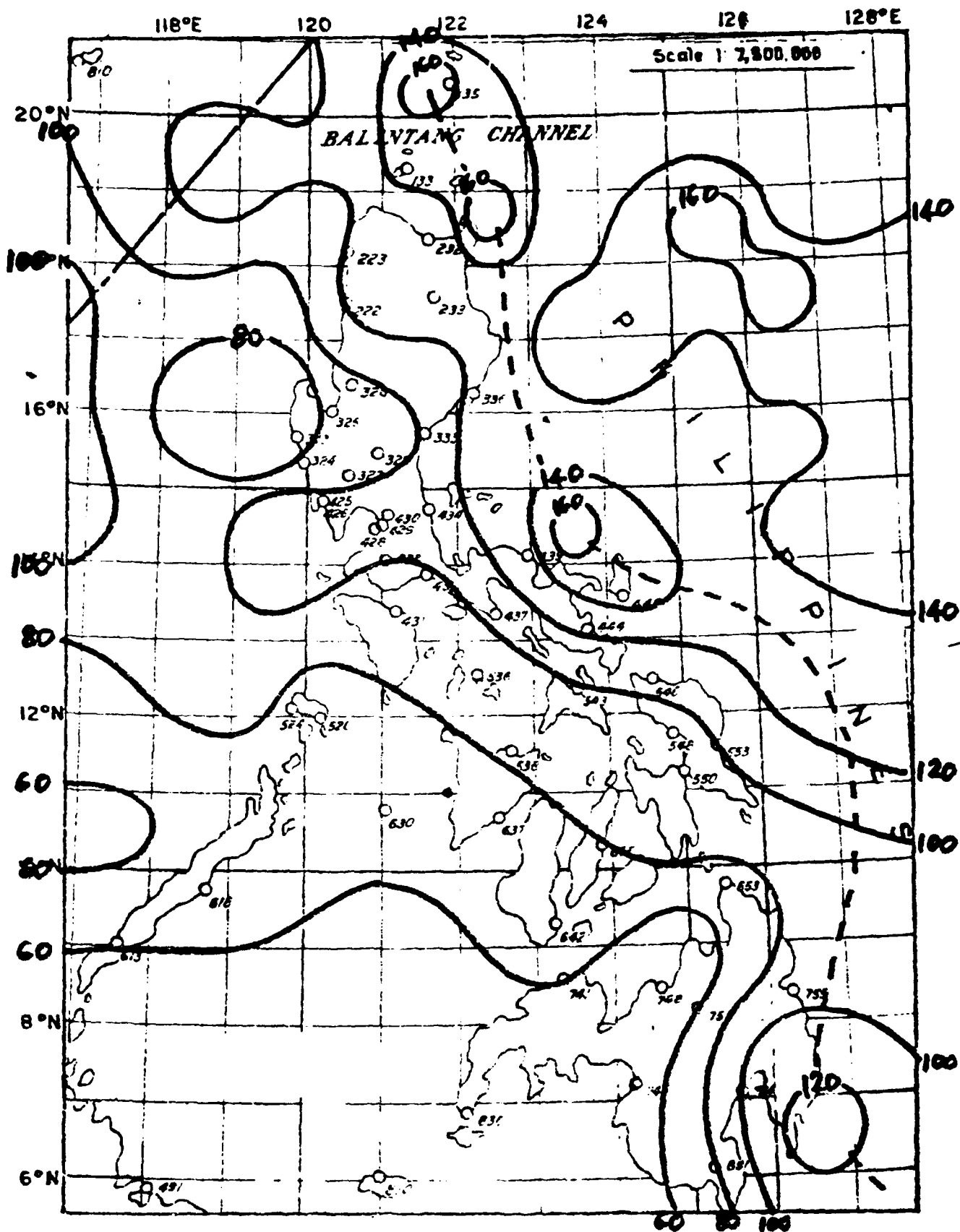


Figure SB-4  
Philippines. Maximum intensity (kt) of passing  
typhoons. Analyzed for each 1° of lat-long  
over period 1950-1978 (from Ref. c).

(gusts to 85 kt) with Subic experiencing only 36-42 kt winds (gusts to 49).

Figure SB-5 (Ref. c) depicts estimated tropical cyclone maximum winds equalled or exceeded once in 50 years. This implies a 50 year storm could produce winds in the Subic Bay area of 150 KPH (greater than 80 kt). An area such as Subic Bay, similar to other protected harbors, would require a typhoon on a "perfect path" to bring the full effects of the typhoon upon the harbor area. Such an occurrence does not seem to have happened over the past 35 years. Patsy (Nov, 1970), a near miss to south, came due west across Luzon and lost intensity from 135 kt to 70 kt (at a position 120 n mi west of Manila), yet still caused gusts to 108 kt at Manila International Airport and gusts to 78 kt at Cubi Point (Ref. 11) and is on record as the most devastating tropical cyclone to strike Manila since 1865.

## 2. Characteristics of Storm Surge

Storm surge has been recorded in Manila Bay and verified at Bagac Bay (see Figure SB-6) 15 miles south of Subic Bay on the Bataan Peninsula (Ref.c). However, although interviews with engineering and U.S. Naval personnel (Refs. h and i) indicate possible storm surge (e.g., high water levels associated with typhoon passage), there were no verifiable records or written reports on past storm surge water levels at Subic Bay. (The Philippine

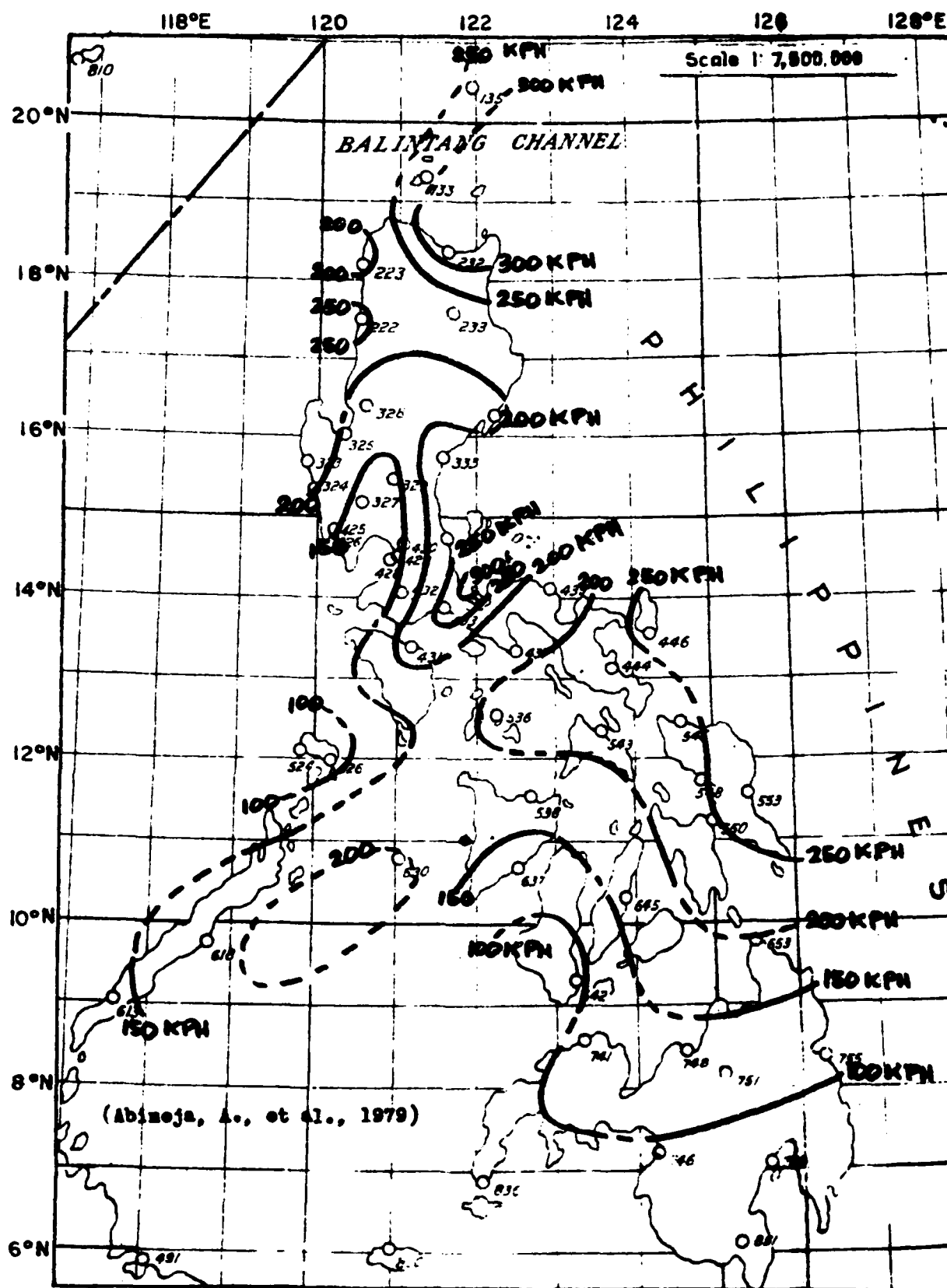


Figure SB-5  
Philippines. Estimated maximum winds (KPH) for passing tropical cyclones to be expected, on the average, once in 50 years. (from Ref. c - taken from: Abinoja, A., et al., 1979, Wind Mapping of the Philippines, NSDB/PAGASA Research Project)

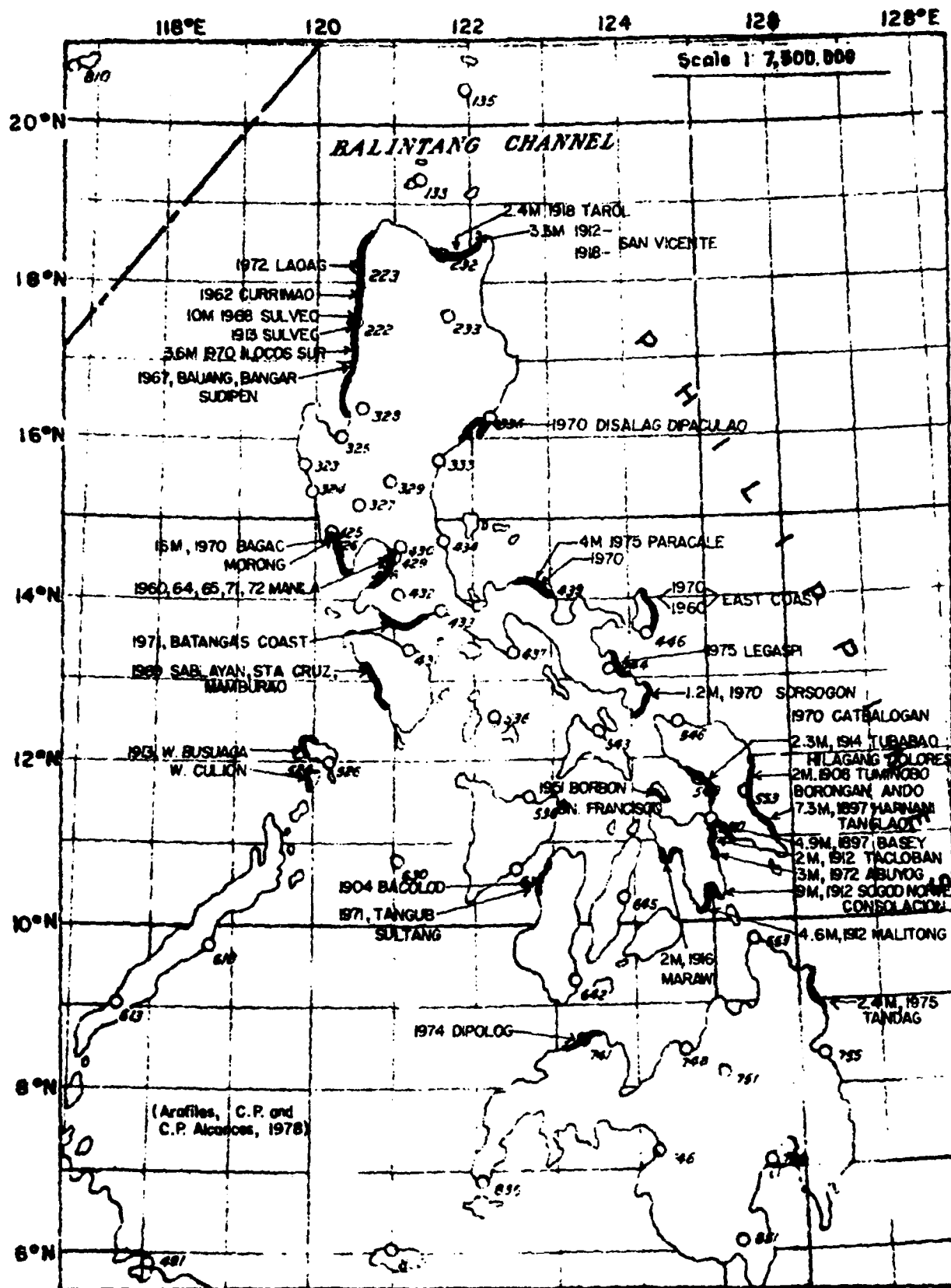


Figure SB-6  
Philippines. Historical storm surge events in the Philippines from 1897 to 1975. (Ref. c - taken from: Arafiles, C.P. and Alcances, C.P., 1978, Storm Surge, Final Report, NSDB/PAGASA, Typhoon Research Project)

Bureau of Coast and Geodetic Survey does not have a tidal gauge in Subic Bay.)

Subic Bay, due to its orientation and topography, is also well protected from most wave action except from a south-southwest wind. Sustained winds of 48 kt (gusts to 60 kt) from that direction caused substantial damage to Alava Wharf (Ref.h) by an aircraft carrier during Typhoon Olga (May, 1976). Significant wave heights of 32 feet could occur at the mouth of Subic Bay with the close passage of an intense typhoon (Ref.j). Brand et al (Ref. 7) determined little or no diminution of wind at the Alava Wharf area for winds 180° to 225°. With a fetch of 6-6 1/2 miles inside the harbor and a depth of 50 feet, 8 foot waves can be generated within the harbor with a south-southwest wind (Ref. 9).

No data or information on seiche within the harbor or tsunami waves was obtained. The normal tidal range for Subic Bay is 3.0 feet with a Mean Tide Level of 1.5 ft.

#### D. Summary

##### 1. Area Impact

Manila Bay has suffered storm surge and severe damage from typhoons on several occasions. Figure SB-6 depicts five years in which storms caused storm surge in Manila Bay. Manila Bay, with its much greater size (26 n mi long, 19 n

mi wide), does not have the topographic protection of Subic Bay. It also has the classic gentle slope, from shore to a depth of about 180 feet, which serves to enhance storm surge. Typhoon Patsy (Nov, 1970) was the most devastating typhoon to strike Manila with 786 killed and close to \$100 million in damage.

Using methods developed by Jelesnianski, Arifiles and Alcances (Ref.a) developed local shoaling factors for 36 basins in the Philippines and determined peak surges for those basins. Using a 56 millibar pressure drop and a maximum wind radius of 15 and 30 miles, a peak surge of 7.5 and 8.5 feet respectively were determined for Manila Bay at Farola Point (10 n mi south of Manila).

## 2. Harbor Impact

Subic Bay, due to its small size and protective topography, requires a typhoon to pass west-southwest of the bay on a northerly (NNE to NNW) heading to cause greatest impact in the harbor area. Those storms which cross Luzon moving due west tend to lose much of their intensity as noted earlier. However, a track as described above is similar to a major axis of most frequent tracks for early season storms (Ref.b).

Those storms which have had the greatest impact upon Subic Bay have passed 15-50 n mi southwest of the bay (Refs. f and h). This places Subic in the strong semi-circle and drives wind and

water into the mouth of the bay (open to the southwest). Subic does not seem to have been subjected to an intense storm on such a track over the 30 year period 1948-1977 (Ref. c). Innundation of the low area east of Port Olongapo was reported (probably due to a combination of surge and flooding) for Patsy (Nov, 1970) and Irma (May, 1966). Both storms also caused inundation of the area just beyond the sea wall (6-7 foot elevation) northwest of Alava Wharf.

### 3. Evaluation

Subic Bay, as Guam, lies on a primary tropical cyclone threat path. The primary direction of approach is from the east resulting in a mitigation of tropical cyclone strength in crossing the mountainous terrain prior to affecting the Subic Bay area. High terrain immediately surrounding Subic Bay further protects the harbor from most storms. However, an intense storm passing south of Luzon (thereby retaining intensity) and then turning northward could pose a serious storm surge threat to Subic Bay. Subic Bay, as Guam, with large Navy assets at low elevation and the potential for serious storm surge should be considered for storm surge modeling.

### III. SITE STUDIES

#### JAPAN

##### A. References and Characterization of Available Data

###### 1. References:

- a. Onuma and Wood Associates, Inc., Architects, Engineers, Planners, 1979: Engineering Services for Hydrographic Survey, Soil Exploration, Site Investigation, Design and Construction Surveillance of Maintenance Dredging for U.S. Fleet Activities, Yokosuka, Japan.
- b. Naval Civil Engineers, 1980: Master Plan for Command Fleet Activity Yokosuka.
- c. Miyazaki, M., 1974: Characteristics of Storm Surges Induced by Typhoons Along the Japanese Coast, Meteorological Research Institute.
- d. Fleet, J.P., Capt. USN and J.J. Erdman, CDR, USN, 1963: Yokosuka Harbor Evaluation.
- e. Isozaki, I., 1970: An Investigation on the Variation of Sea Level Due to Meteorological Disturbances on the Coast of the Japanese Islands, Pap. Met. Geophys., 21, 1-32.
- f. KISHO DAI, 1979: Weather Damage to Okinawa Prefecture, (1948-1977).
- g. Okinawa Prefecture Office, 1977: Damage Bibliography of Okinawa Prefecture (1951-1973).

- h. Graff, R.J., 1975: An Evaluation of the Harbor of Yokosuka, Japan as a Typhoon Haven, ENVPREDRSCHFAC Technical Paper No. 15-75.
- i. Rudolph, D.K., F.J. Blake, S. Brand and J.W. Blelloch, 1975: An Evaluation of the Harbors of Buckner Bay and Naha, Okinawa as Typhoon Havens, ENVPREDRSCHFAC Technical Paper No. 21-75.
- j. Rudolph, D.K., 1975: An Evaluation of Sasebo Harbor, Japan as a Typhoon Haven, ENVPREDRSCHFAC Tech. Paper No.17-75.
- k. Interviews with on-site U.S. Navy personnel including the following typical base units:
  - Naval Civil Engineering
  - Public Works Office
  - Ship Repair Facility
  - Port Operations
  - Facility Staff Planning
  - Naval Oceanography Command
- l. Interviews with on-site local Japanese from following agencies or staffs:
  - Japanese Meteorological Agency
  - Prefecture Meteorological Offices
  - City Emergency Planning Staff
  - City Policy and Planning Staff
  - Harbor and Port Officials
- m. Review of Japanese newspaper articles on typhoon strikes at local site. (Personal collections of Japanese at Sasebo.)

n. DMA Charts:

- 97120 - Tokyo Wan
- 97146 - Yokosuka
- 97396 - Outer Bay of Imari
- 97400 - Sasebo KO
- 97465 - Okinawa Jima
- 97471 - Katchin Wan

o. Other maps:

- Yokosuka General Development Map
- Sasebo Regional and Vicinity Map
- Sasebo Facility Planning Map

2. Characteristics of Available Data

Available data on storm surge information varied widely in scope and value but evaluations of the threat at Yokosuka, Sasebo and Buckner Bay were essentially consistent. Reference data for all three sites was provided by general references 3, 4, 5 and 6 - basically historical, climatological and statistical information. References a through j and m provided site specific information in the form of studies and evaluations. Interviews with U.S. Navy (Ref. k) and local Japanese people (Ref. l) varied widely in value. Generally the Japanese sources proved more valuable due to a much longer time in residence. This was particularly true for those employed in engineering and facility planning by the U.S. Navy and for those involved in local civil planning.

## Yokosuka

### B. Physical Characteristics of Site

#### 1. Geographic Location (Figure Y-1)

Yokosuka is located at 35°17'N, 139°40'E on the east coast of the Miura Peninsula on the southwest side of Tokyo Bay. The Port of Yokosuka and the U.S. Fleet Activities are bounded on the east and south by the peninsula and to the west by an island, Azuma Hanto. The port opens to the north into Yokosuka Bay and thence to Tokyo Bay.

#### 2. Physical Description - Topography and Bathymetry (Figure Y-2)

The land form surrounding Yokosuka is very hilly and offers limited protection from the west with 200-300 foot elevations and from the east with 100-200 foot elevations. Elevations to the south are generally greater than 300 feet. Yokosuka Bay has a narrow (1/2 n mi) mouth into Tokyo Bay to the north with 12 fathom depth. Average waterfront seawall height is approximately 7 feet above MSL.

#### 3. Locations of Structural Development

Figure Y-1 locates the structures associated with U.S. Fleet Activities Yokosuka. There are approximately 640 buildings occupying 4.4 million sq. ft. Ground elevations range 7-10 feet above MSL for most of the facilities.

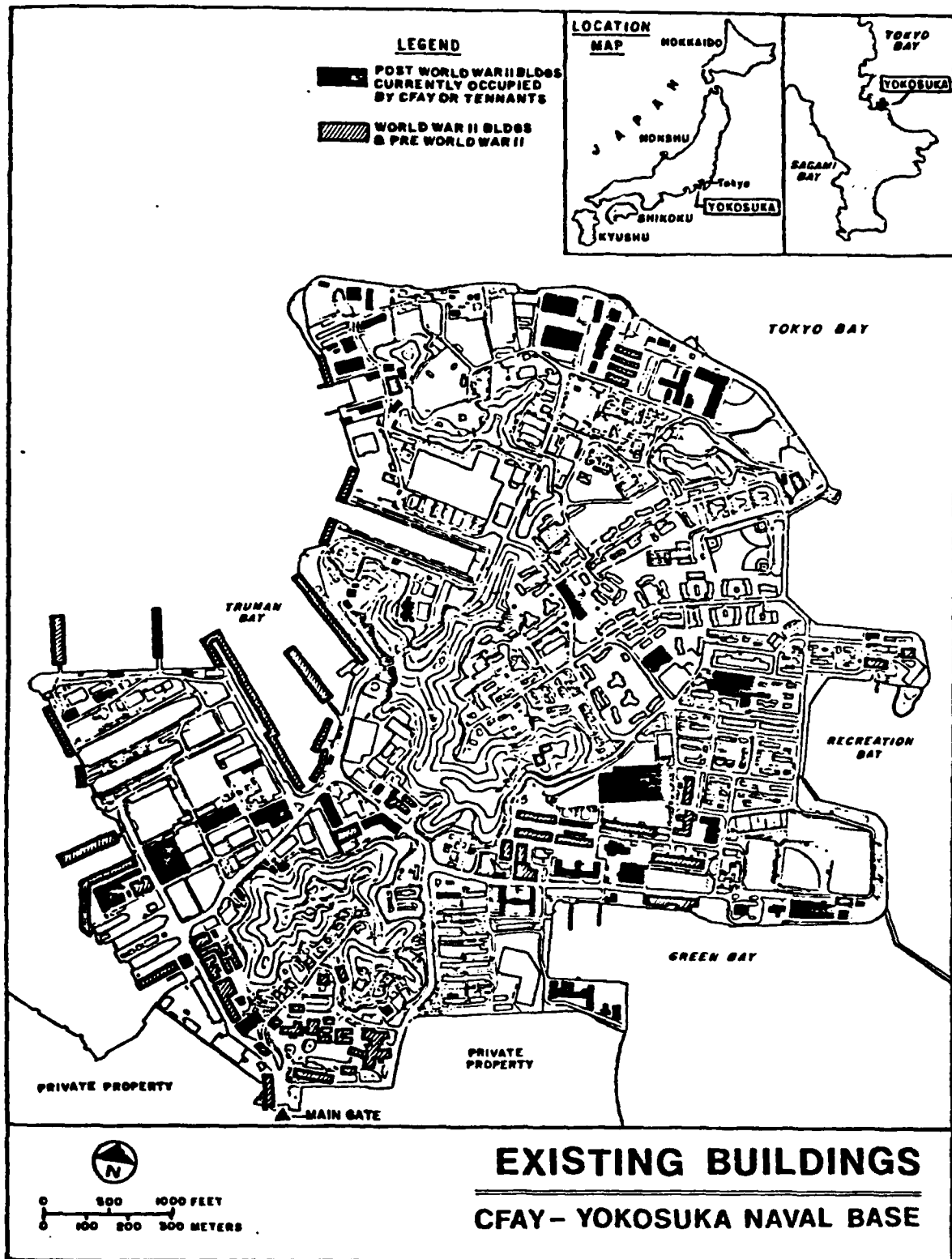


Figure Y-1  
Yokosuka. Location map and structural site locations (from Ref. b).

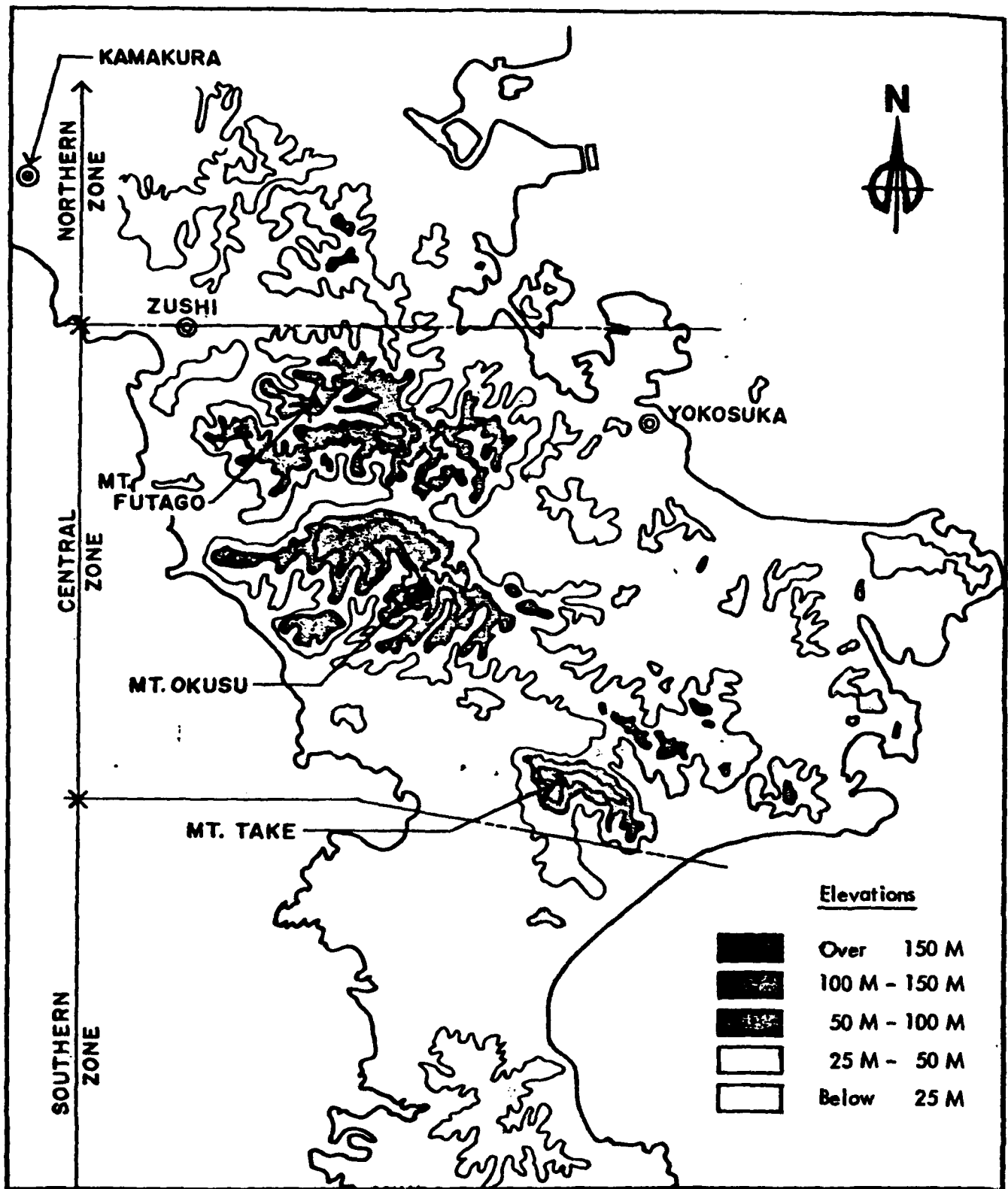


Figure Y-2  
Yokosuka. Topography of Yokosuka area (from Ref. b).

## C. Storm Surge

### 1. Typhoon Frequency and Characteristics

An evaluation (Ref. h) of 27 years of data (1947-73) determined that a total of 82 tropical cyclones passed within 180 n mi of Yokosuka during that period. Analysis of tropical cyclone data on the NCC Tropical Cyclone tape (Ref. 6) over a longer period of 35 years (1945-1979) provided 92 threats within the same threat radius. The average threat to Yokosuka thus is about 2 1/2 to 3 tropical cyclones per year.

At 35° north latitude Yokosuka is located in an area of post recurvature storms. Typically 80 to 90% of the storms which pose a threat have recurved and approached Yokosuka from the SSW (51 of 76 storms or 70%). The typhoons primarily pass east or west of Yokosuka on a NNW heading (Ref. h).

Typical storm paths passing east and west of Yokosuka affect the area quite differently (Fig. Y-3). A path to the west<sup>1</sup> will bring winds from the south across the Miura Peninsula and a path to the east will bring northerly winds off Tokyo Bay with associated wave action. Typhoon Nancy (Sept. 1961), which passed 140 n mi WNW of Yokosuka, caused

---

<sup>1</sup>Approximately 47% of the tropical cyclones passing within the 180 n mi threat radius and caused  $\geq$  22-kt winds at Yokosuka passed to the west of Yokosuka (Ref. h).

gusts of 71 kts from the SSW and sustained winds of 50 kts at Yokosuka. Typhoon Violet (Oct. 1961) with a CPA of 30 n mi to the SE of Yokosuka caused gusts of 74 kts in the harbor. Table Y-1, developed from Japanese Meteorological Agency (JMA) data, depicts typhoon effects in the Yokohama area (17 n mi north of Yokosuka) over a 30 year period. Figure Y-3 depicts the typhoon paths (of Table Y-1) and relates storm passage to the Yokosuka area.

Studies (Refs. c, d, h-j, 3 and 4) and interviews (Refs. k and l) suggest that, although Yokosuka has been subjected to a number of strong typhoons, the location, topography and bathymetry of the area serve to mitigate typhoon effects upon Yokosuka.

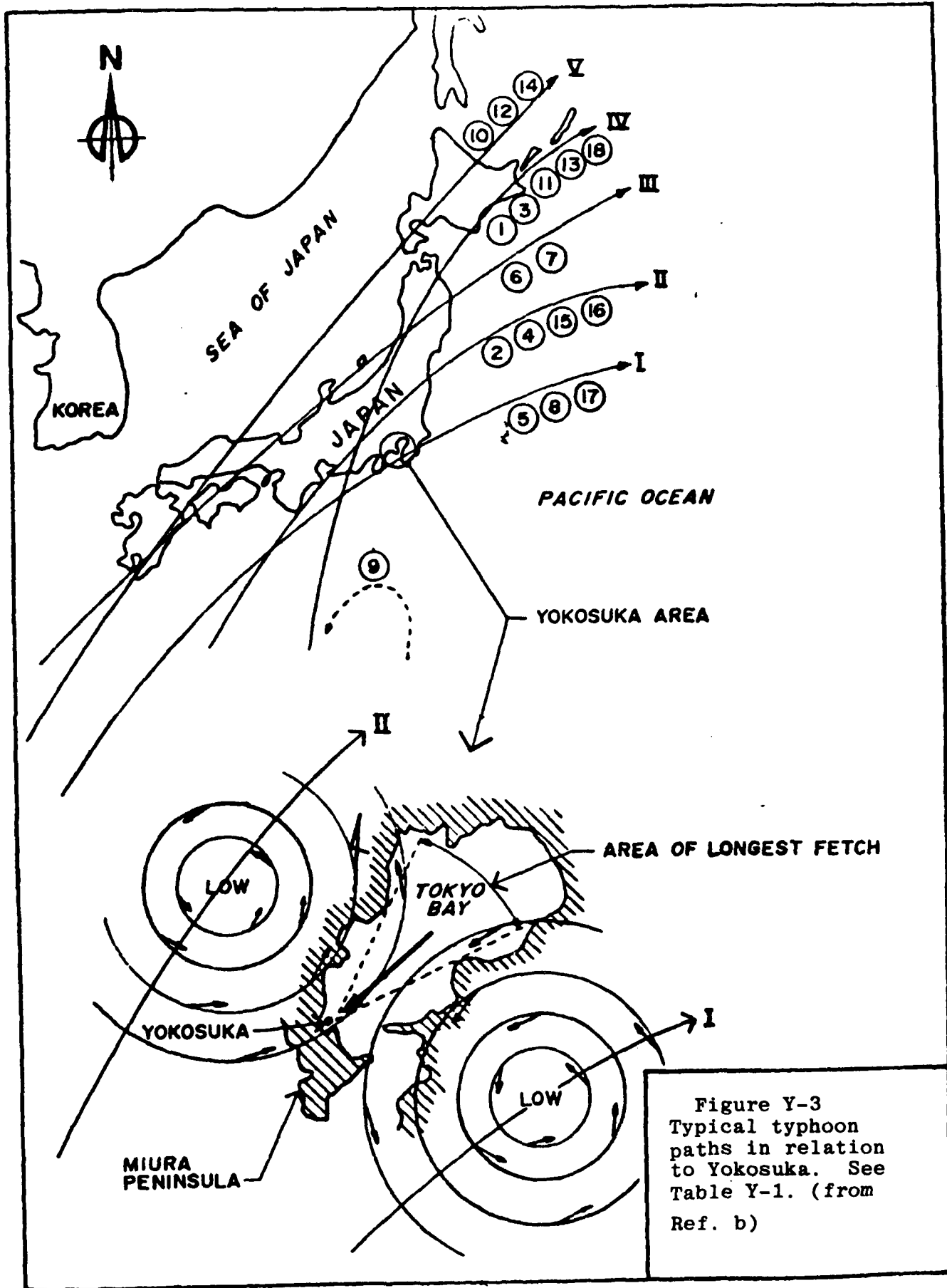


Figure Y-3  
Typical typhoon  
paths in relation  
to Yokosuka. See  
Table Y-1. (from  
Ref. b)

| No. | Date      | Typhoon No.<br>for<br>Year Shown | Data Recorded at Yokohama   |   |                | Maximum Conditions<br>Recorded in Japan           |   |
|-----|-----------|----------------------------------|-----------------------------|---|----------------|---|---|
|     |           |                                  | Pressure<br>in<br>Millibars | Maximum<br>Sustained Wind<br>Velocity<br>(m/sec.) | Wind Direction | Maximum<br>Sustained Wind<br>Velocity<br>(m/sec.) | Maximum<br>Gusting Wind<br>Velocity<br>(m/sec.) |
| 1   | 23 Jun 58 | 11                               | 998.3                       | 29.2  | SSE            | 32  | 47  |
| 2   | 27 Sep 58 | 22                               | 994.0                       | 28.8  | SE             | 38  | 50  |
| 3   | 18 Sep 58 | 21                               | 987.6                       | 26.7  | WNW            | 43  | 54  |
| 4   | 25 Sep 66 | 26                               | 1000.4                      | 26.5  | SSE            | 33  | 51  |
| 5   | 11 Oct 55 | 25                               | 1000.3                      | 25.5  | N              | 30  | 37  |
| 6   | 26 Sep 59 | 15                               | 999.3*                      | 24.4  | SSE            | 42  | 55  |
| 7   | 25 Sep 64 | 20                               | 1003.6                      | 23.3  | SSW            | 50  | 69  |
| 8   | 10 Oct 61 | 24                               | 998.1                       | 23.2  | NNW            | 33  | 47  |
| 9   | 3 Aug 50  | 11                               | 993.3                       | 23.2  | N              | -   | -   |
| 10  | 16 Sep 61 | 18                               | 997.2                       | 22.3  | S              | 67  | 86  |
| 11  | 25 Sep 53 | 13                               | 999.6                       | 22.3  | S              | 33  | 43  |
| 12  | 26 Sep 54 | 15                               | 1002.2                      | 21.7  | S              | 42  | 55  |
| 13  | 18 Sep 65 | 24                               | 999.6                       | 21.7  | SSW            | 33  | 46  |
| 14  | 15 Oct 51 | 15                               | 979.0                       | 21.6  | WSW            | 42.5  | 54  |
| 15  | 27 Sep 56 | 15                               | 1000.6                      | 21.4  | NNW            | 39  | 58  |
| 16  | 24 Jun 52 | 2                                | 984.5                       | 21.0  | W              | 39  | 49  |
| 17  | 19 Sep 54 | 14                               | 1007.3                      | 20.8  | WNW            | 30  | 37  |
| 18  | 19 Oct 79 | 20                               | 977.0                       | 18.8  | SSW            | 44  | 50  |

SELECTED TYPHOON DATA FOR JAPAN

Table Y-1. Yokohama (10 n mi north of Yokosuka) data for significant tropical cyclones from 1950-1979 (from Ref. b).

## 2. Characteristics of Storm Surge

For a typhoon to inflict a maximum surge upon the Yokosuka Bay area it would have to follow a path just east of the harbor at a distance approximately equal to the radius of maximum winds of the storm. This would provide an area of maximum fetch for the winds over Tokyo Bay but would also place the fetch area in the weaker quadrant of the typhoon (Figure Y-3). Typhoon Helen generated surge while on a path closely approximating this optimum. Table Y-2 (from Ref. d) depicts significant storm tide data over a 26-year period (1934-59) for the Tokyo Bay area. Typhoon Helen generated a 2.4 ft storm tide over normal sea at Yokosuka. An optimum storm path with a normal high tide coincident (2 feet over MSL) would still need to generate a surge height of about 5 feet to top the Yokosuka Harbor sea walls - an unlikely occurrence.

The above situation would also generate the maximum wave heights for Yokosuka Bay. The maximum height which would be generated over the fetch (28 n mi) of Tokyo Bay would be less than 7 feet (Ref. b). A similar calculation (Ref. 5) indicated waves up to 9 feet possible with typhoon force winds. Two storms (12 September, 1967 and 24 October 1963) providing northerly winds of approximately 45 mph brought wave heights of 2-4 feet.

| DATE   | YEAR | Max. Wind<br>(Yokohama) | Maximum Tidal Height Over Normal Sea |          |          |          | Name of<br>Typhoon |
|--------|------|-------------------------|--------------------------------------|----------|----------|----------|--------------------|
|        |      |                         | Tokyo                                | Kawasaki | Yokohama | Yokosuka |                    |
|        |      | MPH                     | FT                                   | FT       | FT       | FT       |                    |
| SEP 21 | 1934 | SSW 61.5                | 2.5                                  | - - -    | 1.7      | - - -    |                    |
| SEP 1  | 1938 | S 60.6                  | 4.3                                  | - - -    | 3.1      | - - -    |                    |
| AUG 31 | 1949 | SSE 74.0                | 4.6                                  | - - -    | 2.7      | - - -    | KITTY              |
| SEP 25 | 1953 | S 49.9                  | 3.1                                  | - - -    | - - -    | - - -    |                    |
| SEP 25 | 1954 | S 48.5                  | 2.3                                  | 1.2      | 1.8      | - - -    |                    |
| JUL 23 | 1958 | SSE 65.3                | 3.4                                  | 2.6      | 2.4      | 1.4      | ALICE              |
| SEP 18 | 1958 | ENE 59.7                | 3.0                                  | 2.3      | 2.8      | 2.4      | HELEN              |
| SEP 26 | 1958 | SE 64.4                 | 4.0                                  | 3.1      | 3.1      | - - -    | IDA                |
| SEP 26 | 1959 | SSE 54.6                | 3.7                                  | 3.2      | 2.9      | 2.2      | VERA               |

Table Y-2  
Significant storm surge events for Tokyo Bay for the 26 year  
period, 1934-59 (from Ref. d).

Yokosuka Bay does not appear susceptible to tsunami waves. The earthquake in Chile of 23 May 1960 (8.5 Richter) brought waves of 19-26 ft in height to the Pacific Coast of Japan. However the resultant wave at Yokosuka was approximately 1.5 ft high. Similarly, earthquakes located in and around Tokyo Bay have generated little or no waves at Yokosuka. Actual wave heights observed over a period of approximately 8 years (November 1967 - July 1975) measured no wave higher than 4.9 ft (Ref. b).

Normal tide ranges are 3.2 ft and 4.3 ft for mean and spring tides.

#### D. Summary

##### 1. Area Impact

Tokyo Bay has suffered severe storm surge as detailed in Reference c. The 1 October 1917 storm caused a peak surge of 6.9 ft in Tokyo Bay with a resultant loss of over 1300 lives and more than 60,000 homes lost. Another storm (1 September 1938) caused a peak surge of 7.2 ft in Tokyo Bay. (Past experience with surges has lead to the construction of tidal embankments in Japan thus greatly reducing the danger from storm generated surge.) Due to normal storm paths the northern end of Tokyo Bay is more likely to experience greater surge.

## 2. Yokosuka Harbor

Although storm surge has caused severe damage in nearby Tokyo Bay, the location and configuration of the Yokosuka area has effectively protected the harbor complex over recorded climatological history. Evidence of serious storm surge at Yokosuka was not revealed in any of the source references or in the preliminary literature search. Data from the JMA on typhoon effects in the Tokyo-Yokohama area (Table Y-2) reveal a maximum storm surge of 2.4 feet associated with the 18 September 1958 typhoon (Helen). Conversations with staff civil engineers (Japanese with 30 years local experience) indicated that they had experienced storm surges of an estimated at 2-3 ft range over that period.

## 3. Evaluation

Yokosuka Harbor, located in an area of post recurvature storms, is subjected to threat (<180 n mi) two to three times a year from tropical cyclones. However Yokosuka seems to be protected both by its location and surrounding topography during normal tropical cyclone passage. The storms forward speed may be increased (after recurvature) during its passage; but this poses increased danger to the northern sections of Tokyo Bay rather than to Yokosuka located at the southwest end of the bay. Worst case storm for Yokosuka would probably bring breaking waves over harbor sea walls but severe storm surge is unlikely.

## Sasebo

### B. Physical Characteristics of Site

#### 1. Geographic Location (Figure S-1)

Sasebo is located at 33°10'N, 129°43'E on the northwestern tip of Kyushu, the southern most of the four main islands of Japan. The inner harbor and port are a northern extension of the main Sasebo Harbor which opens, through an intricate island maze, into the Korea Strait to the north, and into the East China Sea to the south.

#### 2. Physical Description - Topography and Bathymetry (Figures S-2 and S-3)

The port of Sasebo is tucked away in the northwestern tip of Kyushu. Surrounded on three sides by steep-sided mountainous terrain, the inner harbor opens to the south into the outer harbor via a narrow 0.6 mile wide harbor mouth of 40 ft depth. Over water fetch, due north, from outer harbor far shore to Sasebo Harbor piers is approximately 6 miles. Outer harbor depths range 40-100 ft while the inner harbor averages 24-40 ft in depth. The Kyushu topography is steep and mountainous providing minimum 100-300 ft heights immediately north, east and west of the inner harbor. Approximately one mile to the north and northeast, the heights go well over 1000 feet. The same is true for the area south of the outer harbor (about two miles from the harbor shore) providing excellent protection for Sasebo Harbor.

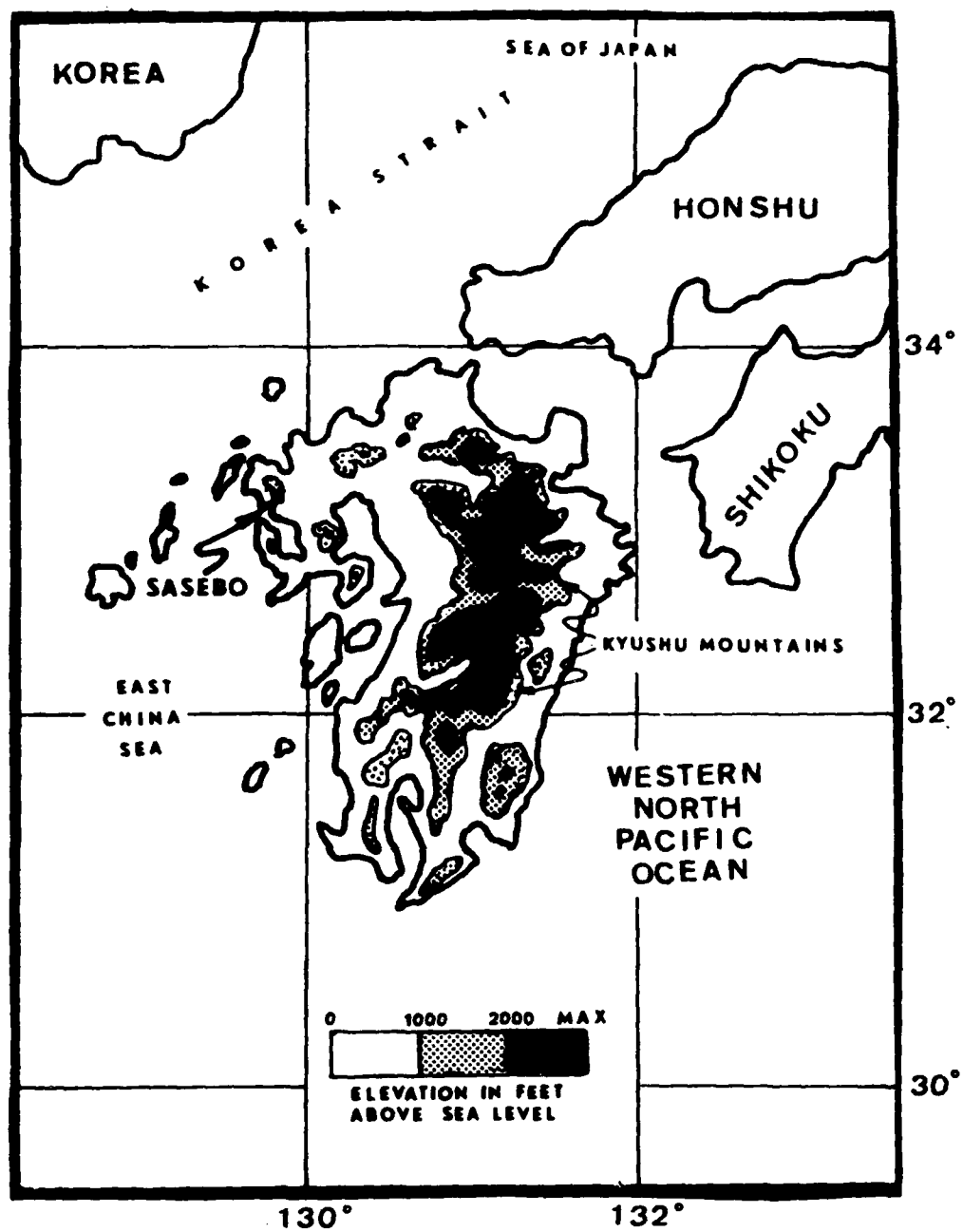


Figure S-1.  
Location of Sasebo Harbor. Topography of  
Kyushu (from Ref. j).

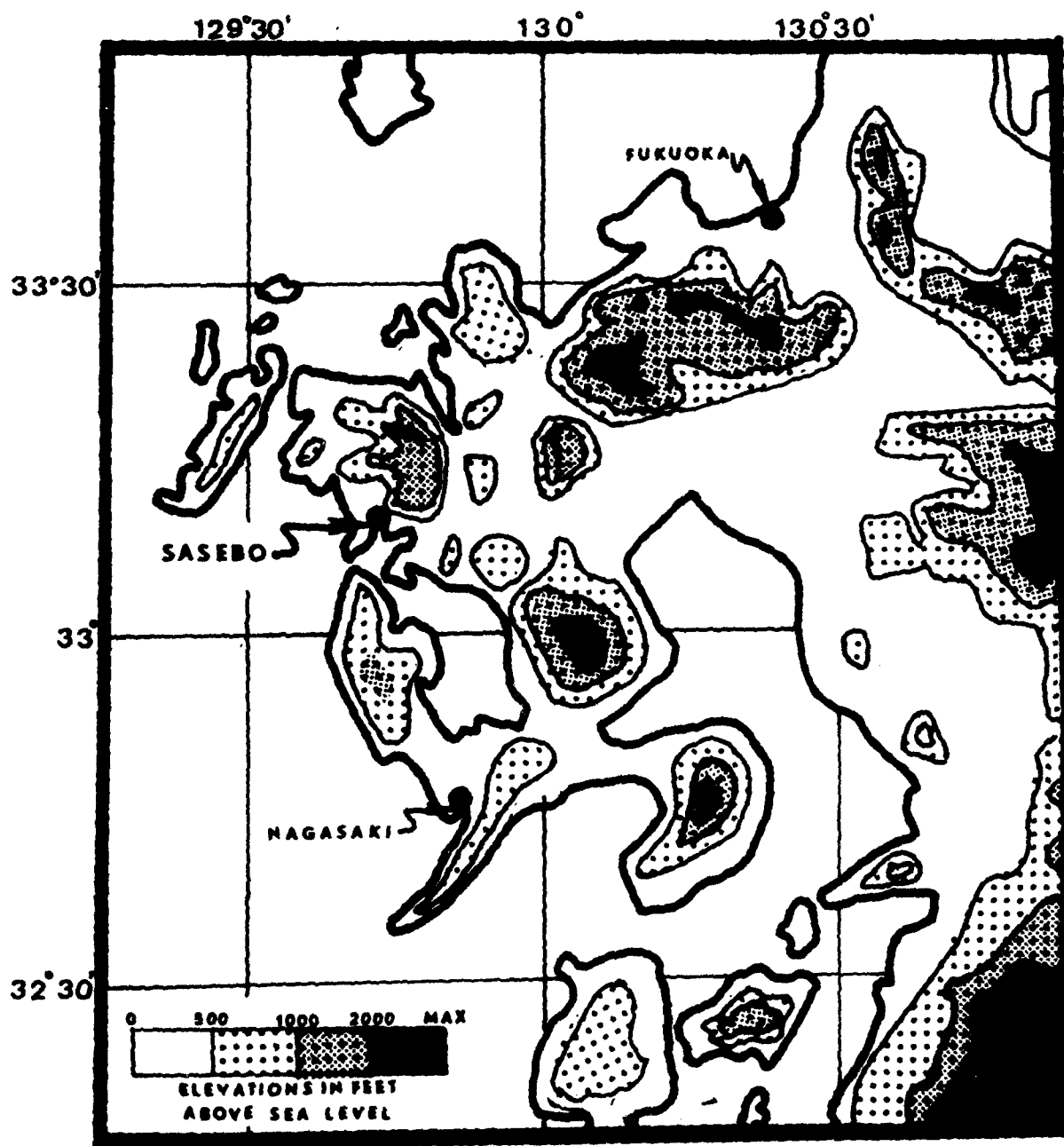


Figure S-2.  
Topography of the northwestern tip of Kyushu  
(from Ref. j).

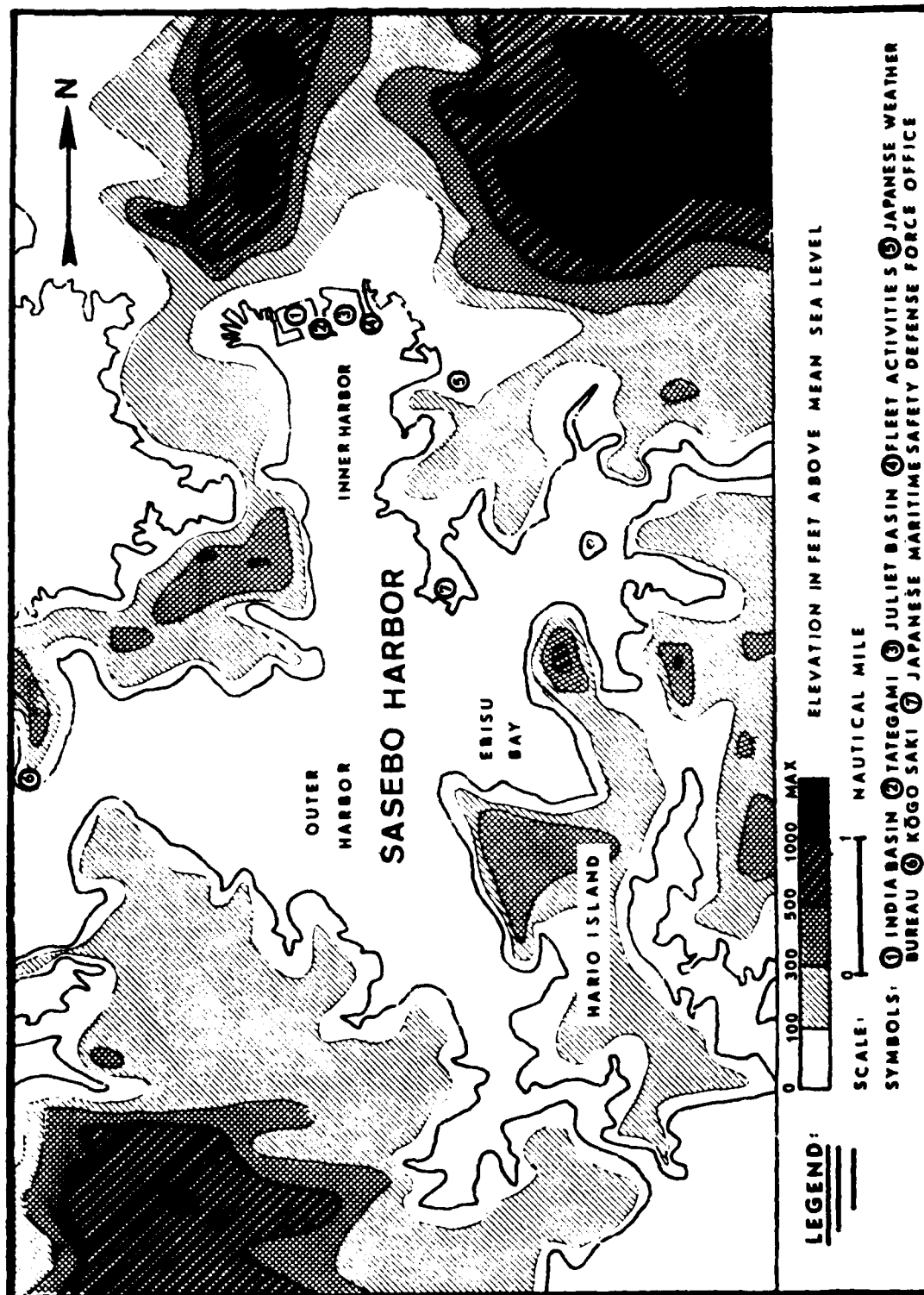


Figure S-3.  
Sasebo Harbor and surrounding topography. Location of structural development (from Ref. j).

### 3. Location of Structural Development (Figure S-3)

The port of Sasebo was established as a naval base in 1886. Prior to and during WWII it was an important ship repair base. Since the war it has become a major commercial and shipbuilding port for the Japanese and is currently used by the Japanese Maritime Self-Defense Force and U.S. Forces Japan (USFJ). The USFJ primarily use Juliet Basin and USFJ structures are located around the perimeter of this basin. The main base area has an average elevation of 13.5 ft above MSL with minimum elevation 9.2 ft above MSL. Average seawall height is 10-12 ft above MSL. Current construction at Sasebo must meet Japanese typhoon construction standards. There were no engineering studies available locally for past construction projects.

## C. Storm Surge

### 1. Typhoon Frequency and Characteristics

From an evaluation of 27 years of data (1947-73) it was determined (Ref. j) that a total of 73 tropical cyclones posed a threat to Sasebo during that period, passing within a 180 n mi radius of the harbor. The NCC Tropical Cyclone tape (Ref. 6) was analyzed for the same threat radius over a 35 year period (1945-1979) and 91 threats were determined; a frequency of about 2.6 tropical cyclones per year.

Sasebo is located at 33° north latitude. This is an area where tropical cyclone recurvature occurs. A high percentage of the storms (65%) are moving north to northeast when entering the threat radius. It was determined (Ref. j) that 57% of its threat storms passed to the east of Sasebo, 37% to the west and 6% dissipated southwest of the harbor. This places the harbor in the left or "weaker" semicircle for the majority of the threat storms - those passing to the east.

Steep mountainous terrain can severely affect tropical cyclone winds upon landfall (Refs. 5, 7 and 8). A 60% reduction in hurricane wind speed can occur within 10 miles after a storm passes from over water to rough terrain (Ref. 8). The terrain surrounding Sasebo harbor is extremely hilly and the approach into the harbor is broken and circuitous. This serves to mitigate winds and storm tides associated with tropical cyclones.

The most dangerous path for a tropical cyclone to follow (producing maximum threat to the harbor) is to approach from the southwest and pass west of Sasebo within 50 n mi or at a distance equal to the radius of maximum wind. This would subject the harbor to the maximum threat possible due to the topographic configuration of the area. A typhoon

(6 July 1974) closely approximated this path passing at 75 n mi to the west-northwest with maximum central winds of 60 kt. Winds of 45 kt were recorded in the inner and outer harbors. Three storms (30 September 1955; 25 September 1968; and 5 August 1971) passing just east of the harbor (50-60 n mi) with central winds of 75, 62, and 50 kt, respectively, created winds of 40-43 kt in the inner harbor.

A study (Ref. j) of 43 tropical cyclones passing within 180 n mi of Sasebo over the 15 year period from 1959 to 1973 determined that about 35% of the storms occurring during the months June-October resulted in gale force winds ( $\geq 34$  kt) in the harbor area.

## 2. Characteristics of Storm Surge

A path just to the west of Sasebo as previously described should produce the maximum surge in the harbor according to current theory. Storm surge at Sasebo has characteristically been weak for passing storms from all documented and verbal accounts. Of 10 tropical cyclones which passed to the west of Sasebo over a 5-year period, the maximum surge observed in the harbor was only 1.3 ft (Ref. j). On-site Japanese civil engineers

with 30-35 years experience in the Sasebo area can remember only two instances (dates unsure as not much damage occurred) when typhoon wind wave action brought water over the tops of the Sasebo Harbor seawalls. The component percentage of surge, tide and wind waves for these two events is unknown.

The Japanese Civil Planning Authority at Sasebo has a strong disaster prevention program. Although Japanese records indicate that typhoons cause flooding and mud slides in the Sasebo area there were no recorded instances of surge over the tidal retaining walls or of flooding due to storm surge.

The maximum wave heights which could be expected at Juliet Basin from typhoon strength ( $\geq 64$  kt) winds from the south are approximately 6-7 ft.<sup>1</sup>

There were no known recorded measurements of seiche or of tsunami waves in the harbor. Tidal ranges are 6.1 ft (mean) and 8.4 ft (spring). Note that it would take an

---

<sup>1</sup>Based on forecasting curves for shallow-water waves from U.S. Army Coastal Engineering Research Center, 1973: "Shore Protection Manual (Volume I)".

unlikely circumstance of high tide and a typhoon passing nearby on the western side of the harbor of significant strength to generate the total wind wave and surge heights to cause water levels to reach seawall heights. Typhoon Gilda (July 1976) followed such a path and caused breaking waves over seawalls.

#### D. Summary

##### 1. Area/Harbor Impact

The primary impact to the Sasebo area from passing typhoons has been deaths and damage caused by heavy rains and mud slides. Mr. Y. Kanda of the Sasebo City Staff (Ref. 1) provided data for the 1945-81 period (37 years) which indicated that five typhoons over that time period caused major impact upon Sasebo. Storm surge was not a causitive factor during those events.

Three case studies (Ref. j) provided evaluations of the effects of typhoons Bess (Aug. 1963), Olive (Aug. 1971), and Gilda (July 1974) upon Sasebo Harbor during passage. Bess passed 65 n mi to the northeast of Sasebo and with center winds of approximately 100 kt caused winds of 38 kt (gusts to 61 kt) at the Japanese Weather Bureau. Olive, with center winds of 65 kt, caused 43 kt winds at the harbor in passage east of Sasebo. Gilda,

passing to the west (CPA 75 n mi west-north-west) with 70-80 kt central winds, caused sustained winds of 45 kt (gusts to 70 kt) from the south. The slow movement of this storm and its optimum position to generate surge and wind waves caused wave action to top the seawalls in the harbor. In all three cases damage was reported as minor and Sasebo was described as a protected harbor. Reference 3 did not identify damage in the area from typhoons not previously considered in this section.

## 2. Evaluation

Sasebo, as Yokosuka, appears to have good protection against possible storm surge from passing tropical cyclones. With an average threat of about 2 1/2 tropical cyclones per year (passing within the 180 n mi radius) and with increased average tropical cyclone forward speed (recurvature latitude) at Sasebo the harbor is certainly susceptible to being subjected to potential storm surge. Yet there is little evidence to suggest a storm surge problem. The extremely mountainous terrain surrounding the harbor and narrow restrictive entrances into outer Sasebo Harbor seem to effectively mitigate storm surge.

## Buckner Bay

### B. Physical Characteristics of Site

#### 1. Geographic Location (Figure B-1)

Buckner Bay (Nakagusuku Wan) is located 26° 15' N, 127° 50' E on the eastern side of the island of Okinawa. Okinawa is the principal island in the Ryuku Island chain which extends in an arc from the southern tip of the island of Kyusku to a point off the northeastern coast of Taiwan. Okinawa is about 350 miles south of Kyusku between the East China and Philippine Seas.

#### 2. Physical Description - Topography and Bathymetry (Figure B-2)

Okinawa is 58 n mi long and 3 to 17 n mi wide. Oriented NE to SW, the northern part of the island is rugged and mountainous. The southern half of the island contains hills and plateaus formed by sloping beds of volcanic ash over older rocks. The area is heavily cultivated. At 26°N the island is located in the warm Kuroshio Current and is surrounded by fringing coral reefs. The hills surrounding Buckner Bay reach over 500 ft heights in some areas but do not offer much wind protection to the bay area.

Buckner Bay is about 9 n mi long (NE to SW) and about 4 n mi wide. An outer area of fringing reef and small islands span almost the entire mouth of the bay offering protection from ocean born wind waves, storm swell

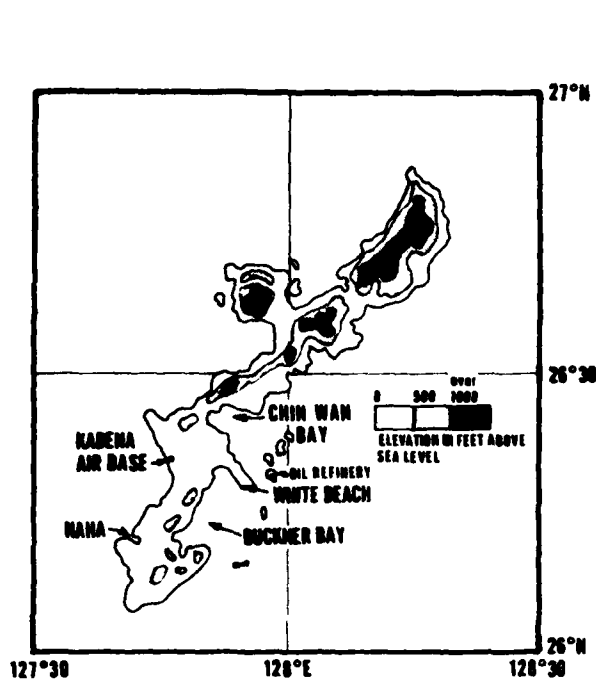


Figure B-1.  
Topography of Okinawa.  
Location of Buckner Bay  
(from Ref. 5).

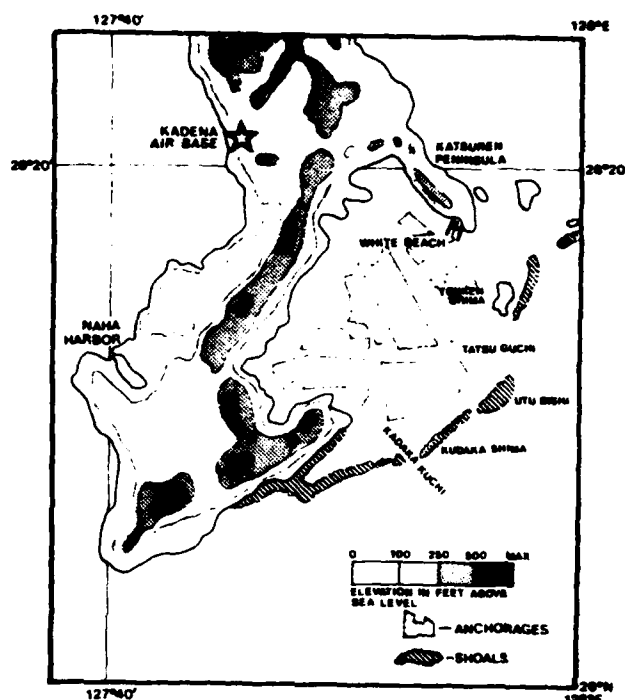


Figure B-2.  
Topography of southern  
Okinawa and Buckner Bay  
(from Ref. 5).

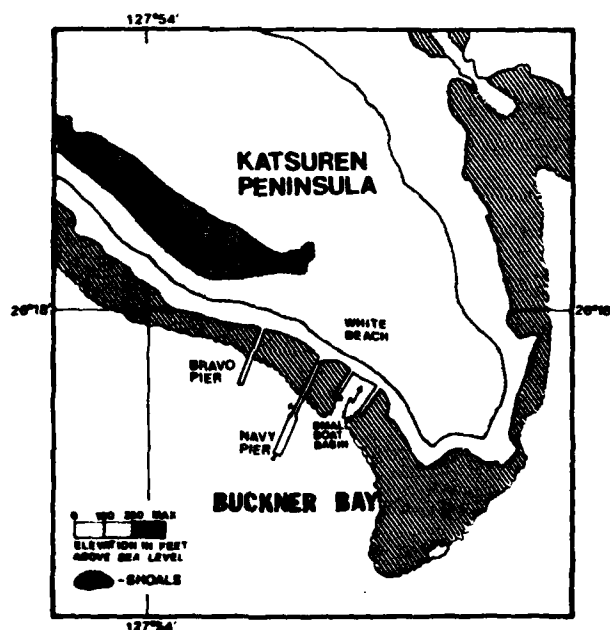


Figure B-3.  
Katsuren Peninsula and  
pier area of White Beach  
(from Ref. 5).

and storm surge. Depths in the harbor range from 120-180 ft. (just inside the barrier reef) to 60-75 ft. over much of the harbor proper. Shoal reefs are heavy in the NW corner of the bay and 500 yd wide (or greater) fringing reefs line the shores of the bay.

### 3. Locations of Structural Development

Figure B-3 depicts the pier areas at White Beach. Structures at the White Beach area are located primarily behind the small boat basin on Katsuren Peninsula. White Beach is used jointly by U.S. Navy vessels and the Japanese Maritime Self Defense Force. Katsuren Peninsula has an average elevation of 100-200 ft. above MSL, and, even at the peninsula's end, most structures are located well above any possible surge or wind wave damage.

## C. Storm Surge

### 1. Typhoon Frequency and Characteristics

In spite of the high frequency of tropical cyclone threat to the Ryukyu Islands, there was very little data available for Okinawa (particularly the Buckner Bay area) from the local office of the JMA. No engineering studies were unearthed at USAF Kadena Air Base (civil engineering responsibility for Buckner Bay) or from Japanese sources.

Okinawa and Buckner Bay are in a zone of high tropical cyclone threat. The island is located close to or within the mean tropical cyclone track for much of the active season. An evaluation (Ref. i) of 27 years of data (1947-73) determined that a total of 115 tropical cyclones passed within the 180 n mi threat radius of a point located mid-way between Buckner Bay and Naha (on the west coast of Okinawa 13 n mi from Buckner Bay). Using a 180 n mi threat radius centered on a point (26° 15'N, 127° 50'E) in Buckner Bay and analyzing the NCC Tropical Cyclone tape for a longer period of 35 years (1945-1979) provided a total of 143 tropical cyclone threats. The average threat to Buckner Bay is about four tropical cyclones per year.

At 26° N, Buckner Bay is in an area in which about 50% of the tropical cyclones which pass within the threat radius are recurving (Ref. i) and therefore have a northeasterly component of motion at their closest point of approach to Buckner Bay. About 75% of the storms approach Buckner Bay from the SE to SW sector with about an equal chance to pass either east or west of the bay.

Due to the relatively low height of the hills and the smooth topographic features surrounding the bay, there is not much mitigation of strong winds over the bay proper. There is

no meteorological observation station located at Buckner Bay. Analyses of Kadena (26° 21'N, 127° 45'E) wind observations (Ref. 5) determined (after "corrected" to Buckner Bay) that about one third of the threat tropical cyclones would produce gale force or higher winds over the bay.

## 2. Characteristics of Storm Surge

Fifty-nine per cent (68 of 115) of the threat tropical cyclones approached Buckner Bay from the south quadrant (Ref. 6). The fact that Buckner Bay is oriented SW to NE and is open in a quadrant from east around to south makes it particularly vulnerable to tropical cyclones approaching from the south. The cyclonic circulation carries wind and storm water directly into the mouth of the bay from the approaching storms. However, the shoaling coral reefs lining the mouth of the bay provide a very effective barrier to tropical cyclone ocean generated wind waves and swell, and to a lesser degree, storm surge. (The height and flow resistance provided by the coral reefs would offer an effective barrier to events of short duration.)

Actual data found to verify the effects of tropical cyclones upon Buckner Bay, was very limited. The lack of any meteorological or oceanographic (tidal) recording station in or next to the bay and the fact that no related

studies could be found in literature or on file with U.S. (Ref. i an exception) or Japanese officials on Okinawa left only "local" knowledge to verify tropical cyclone effects upon the bay area.

According to statistical information gathered by the U.S. Naval Oceanographic Office (Ref. i) a maximum storm surge of 7.8 ft. can be expected in the bay. The maximum wave heights that could be expected within the bay with typhoon strength winds ( $\geq 64$  kt) and 9 n mi fetch would be about 9-10 ft (Ref. 9). Wind waves generated outside the harbor area could be expected to be of much greater magnitude but would also be greatly reduced by the shoaling reefs.

There was no available data on tsunami wave occurrence or seiche action in the harbor. Tidal ranges are 4.1 ft. (mean) and 5.4 ft. (spring).

#### D. Summary

##### 1. Area/Harbor Impact

In spite of the apparent high vulnerability of Buckner Bay (i.e., frequency of threat and large E to S bay mouth opening) to tropical cyclone threat, very little data could be found to substantiate any severe damage to the area caused by typhoons. Interviews with public works civil engineers (on Kadena Air Base) responsible for construction, repair

and maintenance of the U.S. Navy facilities at White Beach did not reveal any major repairs to the area from typhoon-caused damage. Interviews with on-site U.S. Navy hired personnel did not provide any information on past damage and indicated storms generally did not severely affect the White Beach area. (This must be weighted lightly due to the short, five year residence of the interviewee.)

Some information available through the local JMA Prefecture Office (Ref. 1) indicated that over a 30 year period (1948-77) two storms of record (July 24, 1972 and Sept 9, 1976) produced areas of storm surge in Buckner Bay. Another document (Ref. g) indicated that a storm (October 13, 1951) created storm surge of 10-16 ft along the east coast of Okinawa but only 5 ft maximum on the northwest (Awashi) shore area of Buckner Bay. This would indicate a highly effective barrier in the shoaling reefs outside the bay entrance. This storm passed 41 n mi west of Buckner Bay with center winds of 90 kt.

## 2. Evaluation

Buckner Bay is located in a zone of high tropical cyclone threat. Of the nine sites studied Buckner Bay was subject to the highest threat frequency from typhoons. It also is susceptible to more severe storms (i.e., higher maximum winds) than most of the sites. The bay is open in a large arc from the east

around to the south. All of the above suggest a high threat probability of tropical cyclone generated storm surge yet little evidence was found to support high storm surge levels associated with past tropical cyclones. Typhoons which generated high storm surge along the southern and southeast coast of Okinawa did not do so in Buckner Bay.

### III. SITE STUDIES

#### DIEGO GARCIA

##### A. References and Characterization of Available Data

###### 1. References

- a. Lyon Associates, Inc., 1976: Climatic and Oceanographic Conditions, Diego Garcia, B.I.O.T.
- b. Moffett and Nichol, Engineers, 1980: Waterfront Facilities - Diego Garcia, Concept Study.
- c. Tropical Cyclone History, Diego Garcia BIOT.
- d. Naval Weather Service Detachment, 1978: Station Climatic Summary, Diego Garcia, (Period Jan 51-Dec 77).
- e. Department of the Navy, NOCD, Astronomical Data-Tide Tables (1982), Diego Garcia, BIOT.
- f. Telephone interview with Navy NOCD personnel.
- g. Charts DMA
  - 61610 (Chagos Archipelago)
  - 61611 (Diego Garcia)

2. A visit to Diego Garcia was not made. A telephone interview (Ref. f) with on-site personnel indicated a lack of historical data on the island and no one on the island with memory of past storm events.

References a and b are studies for new facility construction on Diego Garcia and contain climatic and oceanographic evaluations. References c, d and e contain historical, climatological and current tidal data, respectively. Tropical cyclone tracks and other storm parameters were extracted from Reference 6. Reference 5 contains statistical data and an evaluation of the typhoon threat to Diego Garcia over a 31 year period.

B. Physical Characteristics of Site

1. Geographic Location (Figure DG-1)

Diego Garcia is located in the southern Indian Ocean at 7°18' South Latitude and 74°24' East Longitude. It is the southernmost island in the Chagos Archipelago and lies approximately 1200 n mi south of the tip of India.

2. Physical Description - Topography and Bathymetry (Figure DG-2)

Diego Garcia is a low horseshoe-shaped coral atoll approximately 37 miles long and 1 mile wide at its widest point. The atoll opens to the north, has little land mass (approximately 11 square miles) and is low with maximum elevation 10 feet above mean sea level. Lagoon depths average from 60 to 100 feet. Seaward, the slope of the sea floor is steep and depths increase rapidly to several hundred feet.

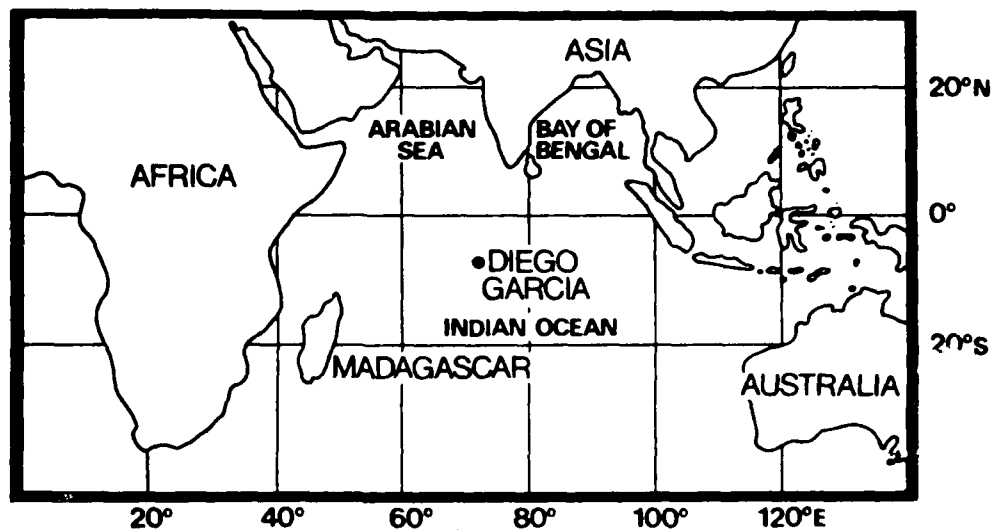


Figure DG-1.  
Location of Diego Garcia (from Ref. 5).

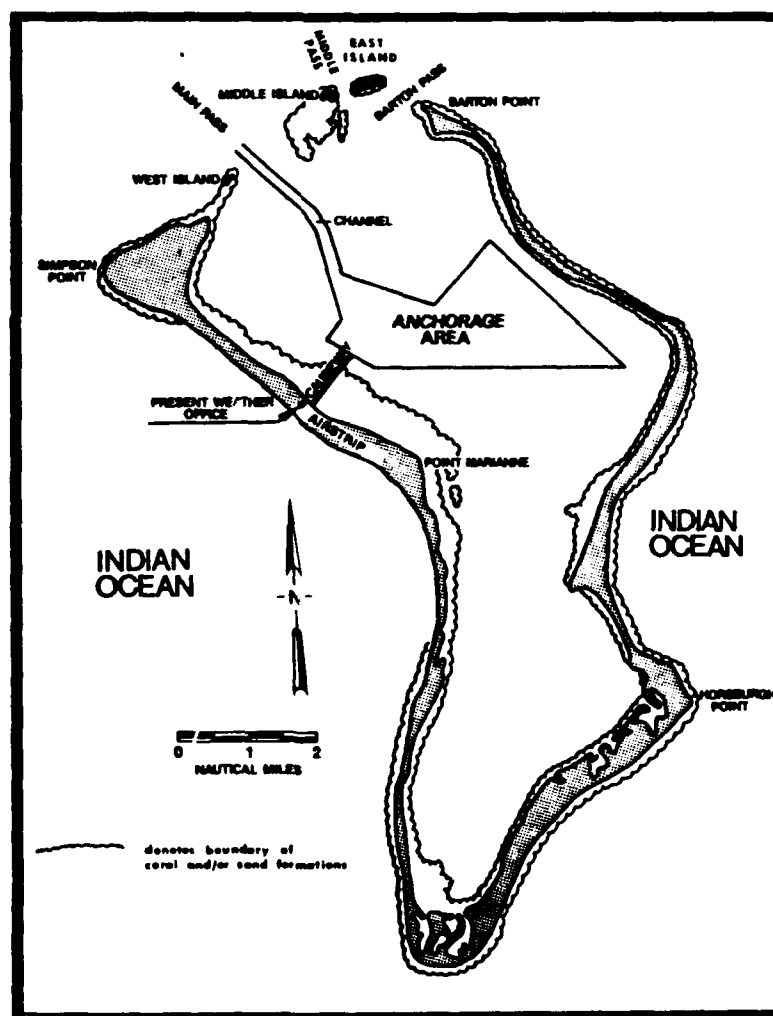


Figure DG-2.  
Diego Garcia atoll (from Ref. 5).

### 3. Locations of Structural Development

Construction at Diego Garcia appears to be primarily limited to the NW arm of the atoll from Point Marianne to Simpson Point. Early naval construction was performed by the Naval Construction Battalion Forces (SeaBees). Current and planned construction are improvements to naval and flight facilities and construction of new support facilities.

## C. Storm Surge

### 1. Typhoon Frequency and Characteristics

Reference 5 contained an evaluation of tropical cyclone threat frequency based on 31 years of data (1944-1971/1973-1976). Using 180 n mi as a threat radius, 33 tropical cyclones posed a threat to Diego Garcia over the 31 year period or about 1 per year.

Diego Garcia at 7°S is considered in an area of tropical cyclone formation rather than a zone of dangerous storm paths. This has been verified by data from references a, b, c, f, 5 and 6. The maximum sustained wind at Diego Garcia attributed to a tropical cyclone during the last 30 years was approximately 40 kts (Ref. 5). Reference c verifies this information suggesting gusts in excess of 60 knots were associated with the same storm

of September 1944. Reference b states that only 13 per cent of the 22 cyclones (1939-1969) that passed within the 180 n mi radius had sustained winds between 32 and 42 knots associated with them, indicating generally weak storms or storms early in their generation stage.

A storm track that would pose the greatest potential danger to Diego Garcia would pass directly over the island or just to the north. This would force wind waves and possible surge through the open mouth of the lagoon (Figure DG-2). However, since 80% of the tropical cyclones in the 31 year period (1944-71/1973-1976) developed or passed to the south, strong northerly winds would be extremely rare (Ref. 5). The return period for extreme winds are presented in Table DG-1 (Ref. a). These were developed considering tropical cyclone frequency and characteristics.

Table DG-1 (from Ref. a)

Return Period for Extreme Wind Speeds

| <u>Return Period</u> | <u>Sustained Wind</u> | <u>Instantaneous (Gust)</u> |
|----------------------|-----------------------|-----------------------------|
| 10                   | 40 knots              | 56 knots                    |
| 25                   | 45 knots              | 63 knots                    |
| 50                   | 49 knots              | 69 knots                    |
| 100                  | 53 knots              | 74 knots                    |

## 2. Characteristics of Storm Surge

Storm surge has not proven to be a threat to Diego Garcia over its recorded climatological history. This can be contributed to two facts: the lack of a tropical cyclone of substantial strength near the atoll, and the bathymetric configuration which would tend to mitigate any potential storm surge. Frequency and intensity of tropical cyclones within threat distance (180 n mi radius) was previously discussed. Deep ocean atolls with steep sea slopes will normally dissipate the dangerous pile up of wind driven water that is associated with storm surge. Table DG-2 (Ref. a) gives maximum still water levels<sup>1</sup> above hydrographic datum. The return periods represent the combination of the probability of occurrence of storm surge and an astronomical tide level equal to or greater than Mean High Water.

Table DG-2 (from Ref. a)

Maximum Still Water Level Above Hydrographic Datum

| Return Period  | Storm Surge   | Astronomical Tide | Total SWL     |
|----------------|---------------|-------------------|---------------|
| <u>(Years)</u> | <u>(Feet)</u> | <u>(Feet)</u>     | <u>(Feet)</u> |
| 64             | 0.5           | 5.1               | 5.6           |
| 128            | 0.6           | 5.1               | 5.7           |
| 320            | 0.7           | 5.1               | 5.8           |

<sup>1</sup>Still water level (SWL) is defined as the level of a water body assuming no waves are present.

Though storm surge does not appear to be a threat, there are at least two situations which, if not likely, are at least possible which could cause damage on Diego Garcia. The passage of a storm of sufficient strength to cause a storm wave (not surge) of sufficient height to wash over the atoll or the passage of a storm near typhoon strength in a path over the atoll (or just north) which could force a surge through the mouth of the lagoon.

Seiche within the lagoon basin was found to be negligible (Ref. a). Normal tidal ranges are 3.8 and 5.5 feet for mean and spring tides.

#### D. Summary

##### 1. General Area/Harbor Impact

With the single exception of the September, 1944 storm, passing tropical cyclones have had negligible effect upon Diego Garcia. The 1944 storm inflicted sustained 35-40 knot winds with estimated 60 knot gusts. Two Catalina Flying Boats were destroyed and several hundred coconut palms were knocked down or stripped bare (Ref. c).

##### 2. Evaluation

Storm surge does not appear to be a threat to Diego Garcia. Located in an area of tropical cyclone formation at 7°S Diego Garcia is not subjected to fully developed tropical cyclones. This is supported by the historical

data found. Statistical evaluations place storm surge at approximately 1/2 ft for a 60-100 year return period. This is negligible compared to normal tidal changes.

### III. SITE STUDIES

#### KOREA

##### A. References and Characterization of Available Data

###### 1. References

- a. Lyon Associates, Inc., Consultation Engineers and Korea Institute of Science and Technology and Korea Engineering Consultants Corporation, 1981: Korea Port Phase Three Development Study.
- b. Nestor, M.J.R., LCDR RN, 1977: The Environment of South Korea and Adjacent Sea Areas; NAVENVPREDRSCHFAC Technical Report TR 77-03, 284 pp.
- c. Choi, B.H., 1980: Tidal Analysis of Incheon for the Years 1962-1972/1975-1977, KORDI Report 80-01.
- d. Hwang, C., 1971: On the Variation of Sea Level Due to Meteorological Disturbances on the Coast of Korea. I. Storm Surges Caused by Typhoon Billie, 1970, on the West and South Coasts of Korea, Journal of the Oceanological Society of Korea, Vol. 6, No. 2, pp. 92-98.
- e. Rudolph, D.K., 1975: An Evaluation of the Harbors of Incheon, Pusan, and Chinhae, Republic of Korea as Typhoon Havens, NAVENVPREDRSCHFAC Technical Paper No. 22-75.
- f. Hydrographic Office Seoul, Korea, Hydrographic records and storm surge data.
- g. Chu, K.S., Personal storm surge data and calculations.
- h. Ahn, Myong-Bok, Personal storm surge calculations.

i. Interviews with U.S. Navy and U.S. Air Force personnel including the following typical units:

- Naval Civil Engineering
- Facility Staff Planning
- Meteorological Forecast Units
- Port Operations
- Military Sealift Command

j. Interviews with local Koreans from the following agencies or staffs:

- Central Meteorological Office
- District Meteorological Offices
- Hydrographic Office
- Harbor and Port Officials
- Engineering Consultants Corporation

k. Interviews with U.S. engineers at Lyon Associates, Inc.; Pusan, Korea.

1. DMA Charts

- N0-95067 - Inchon Hang
- N0-95146 - Chinhae Man
- N0-95148 - Chinhae Hang
- N0-95151 - Pusan Hang
- N0-95060 - Korea West Coast
- N0-95140 - Korea South Coast

2. Characterization of Available Data

Available data on storm surge in Korea was restricted to post WWII years and although tidal gauges have been installed in many areas during those years the records are broken. Movement of some gauges to achieve more representative tide and surge readings (i.e., at Chinhae, Pohang, others) has also occurred.

Again, as at other sites, the tidal gauges tend to fail when most needed as at Pusan with Typhoon Sarah in September 1959.

Little published data on storm surge for the sites of Inchon, Pusan, and Chinhae in Korea was found (Ref. d is an exception). Most of the storm surge data and analysis for the three sites in Korea proved to be personal data and analysis by government officials within the meteorological and hydrographic offices (Refs. g and h). References a, b, and c provided background and technical data on the environment of South Korea. Reference f proved of limited use as most analyzed data dealt with maximum monthly tidal heights (i.e., astronomical tide plus deviation) which were primarily due to astronomical tides.

Interviews with Korean meteorologists and oceanographers proved of value only in a negative sense as few major storm surge events in any of the three sites could be recalled (Sarah, Sept. 1959 was an exception - however no recorded data for Sarah at Pusan was available).

## Inchon

### B. Physical Characteristics of Site

#### 1. Geographic Location (Figure I-1)

Inchon is located at 37°28'N, 126°37'E on the western coast of the Korean Peninsula about 20 mi west of Seoul. The harbor complex is built around the estuary of the Yom Ha River, a southern tributary of the Han River. Inchon Harbor is bordered on the west by the Yellow Sea and several offshore islands.

#### 2. Physical Description - Topography and Bathymetry (Figure I-2)

The Port of Inchon is in an area of geological submergence (Ref. b) characterized by many peninsulas and bays and hundreds of islands. It is surrounded by broad valleys and by low hills with decreasing elevations toward the Yellow Sea. The area around Inchon is a shallow tidal basin with vast expanses of mud flats which are exposed during low tide. The Yellow Sea itself is a very shallow basin with average sea depths of 150 ft (maximum depths of approximately 300 ft). The outer harbor at Inchon is essentially a section of the Yom River with average depths 30-45 ft. Inchon Harbor is surrounded by low hills of 300-400 ft heights.

#### 3. Locations of Structural Development

The U.S. does not have any facilities at Inchon Harbor. The U.S. Navy occasionally uses anchorage areas in the Yom River. Inchon

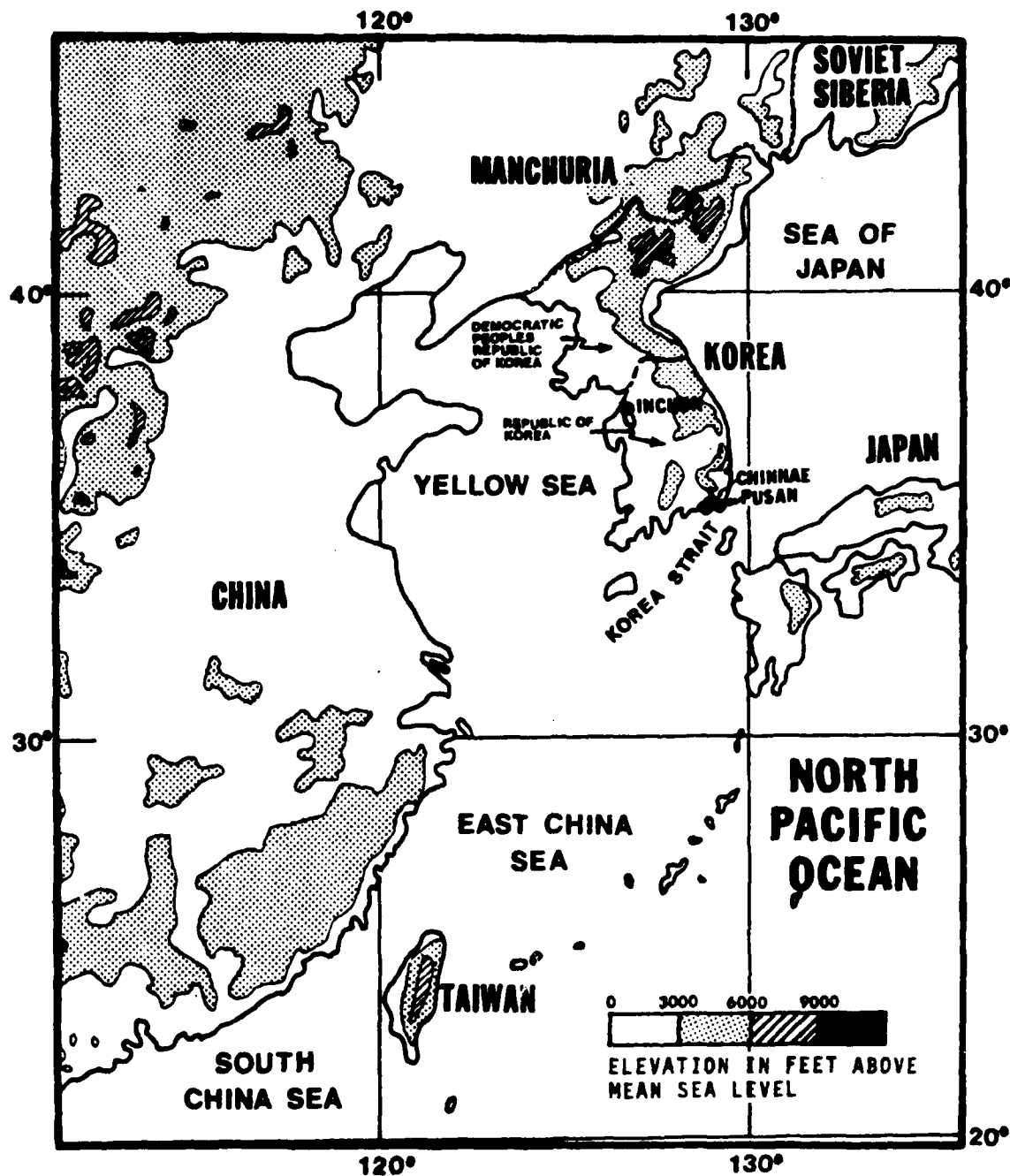


Figure I-1.  
Locator map of the western North Pacific Ocean  
showing the positions and topographies of major  
land masses (from Ref. e).

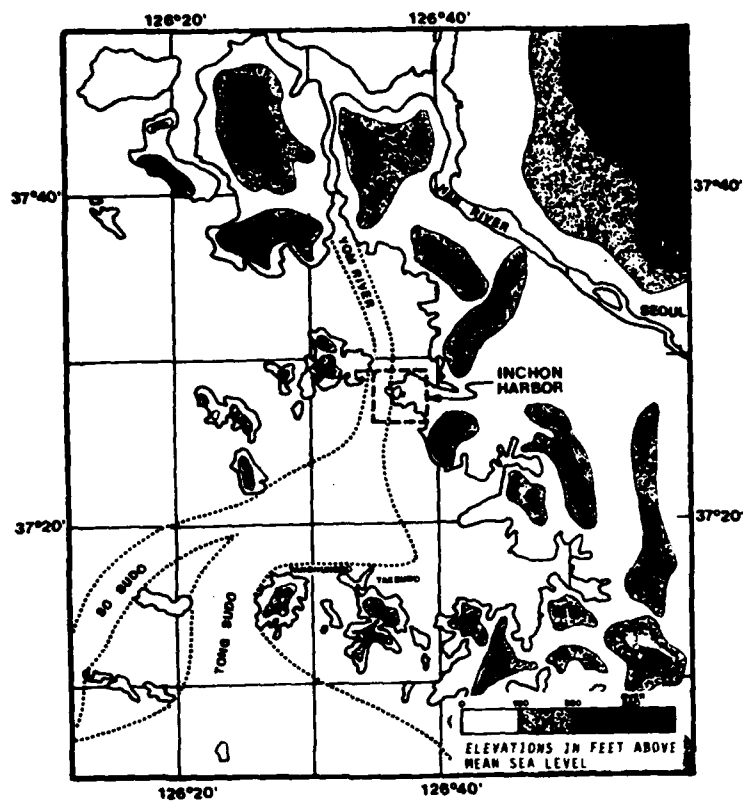


Figure I-2.  
Mesoscale topography and geographic  
location of Incheon Harbor (from Ref.  
5).

serves as the commercial outlet and port of entry for Seoul. The Port of Incheon is built from reclaimed land and is an extension of the city of Incheon primarily on the west and south sides of the Incheon Peninsula.

### C. Storm Surge

#### 1. Tropical Cyclone Frequency and Characteristics

Tropical cyclone threat frequency was determined (Ref.e) for a 27-year period (1947-1973) in which 36 tropical cyclones approached to within 180 n mi of Incheon Harbor. Thus there is an average threat of four tropical cyclones every three years.

Tropical cyclones are usually in a weakening stage of storm dissipation by the time they reach Incheon, therefore have central wind speeds generally of 45-60 kt. There is the possibility of some storms following a path that would take them over mainland China and then near Incheon on a recurvature path. This would allow reintensification over the warm waters of the Yellow Sea. However, past history at Incheon suggests that, even in these cases, wind speeds will be substantially less than typhoon strength. In fact over a 35-year period (1945-1979) only two storms were recorded with  $\geq 64$  kt maximum winds within the

180 n mi radius of Inchon. Gale force (>33 kt) winds at Inchon were produced in only nine cases over the 27-year analysis period (Ref. e) and on no occasion did the maximum sustained wind exceed 50 kt at Inchon.

Tropical cyclones approaching Inchon do so primarily from the S or SW (58%). Paths tend to be SW to NE placing the tropical cyclone basically east or west of Inchon at passage. The cyclonic circulation would therefore cause predominantly northerly winds from an eastern passage and southerly winds from a western passage. A passage to the west would bring winds from the more dangerous side of the storm to the least protected SW quadrant of Inchon as well as allow the tropical cyclone to maintain an over water path longer (therefore maintain intensity longer). This is considered the more dangerous path for generation of strongest winds and storm surge.

## 2. Characteristics of Storm Surge

The characteristics of a storm producing a maximum surge at Inchon should be those of a tropical cyclone passing just to the west of Inchon as previously described. Analysis of tidal station hydrographic data (Ref. g) over a 19-year period (1963-81) provided storm surge data on four tropical cyclones which produced surge greater than 1.6 ft at Inchon.

AD-A128,796

EVALUATION OF US NAVY TROPICAL CYCLONE STORM SURGE  
REQUIREMENTS IN THE WE... (U) SCIENCE APPLICATIONS INC  
MONTEREY CA A J COMPTON FEB 83 SAI-PN-1-425-02-423  
NEPRF-CR-83-02 N00228-81-C-H551 F/G 15/3

22

UNCLASSIFIED

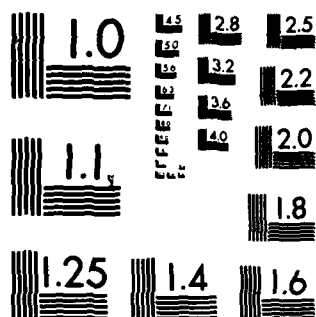
NL

END

DATE

FILED

DTIC



MICROCOPY RESOLUTION TEST CHART  
NATIONAL BUREAU OF STANDARDS-1963-A

The tidal difference attributed to surge ranged from 1.8 ft to 2.7 ft. Another study (Ref. h) over a similar period (1960-78), which dealt with collection and analysis of storm surge data in Korea, showed that storm surge was the causitive factor in less than 10% of the cases of extreme high water. Also, for the 19-year period, there were only three cases in all of Korea in which storm surge greater than one meter in height was measured.

Typhoon Billie (31 Aug 1970) produced a surge of 2.6 ft over predicted tide (Ref.d) at Inchon. At the time of maximum surge at Inchon the maximum winds for Billie were estimated at 50 kt with the storm center approximately 70 n mi SW of Inchon. This placed Billie close to the optimum path to produce a strong storm surge at Inchon.

Due to the characteristically shallow depth of the Yellow Sea and Inchon Harbor there are large astronomical tidal changes at Inchon (>20 ft). It is not unusual for a tropical cyclone to cause a large negative surge at Inchon prior to arrival. (A 2 ft negative deviation preceded the positive surge at Inchon for Typhoon Billie.) The combination of characteristically weakened tropical

cyclones and the large dynamic changes in normal astronomical tides probably tend to mitigate most storm surge at Inchon. Reference c contains an analysis of the probability of a combination of astronomical tide and storm surge and determined an extreme 100 year height of 32.8 ft for the combined tide-surge probability. Mean tide level is 15.2 ft for Inchon with 20.7 ft as mean tide range and 27.1 spring range.

Maximum wind wave heights that can be expected with typhoon strength winds ( $\geq 64$  kt) are about 5-6 ft with a northerly wind and 7-8 ft from a southerly wind for the outer harbor (Ref. e).

Due to the location, shape and surrounding bathymetry, seiche and tsunamis are not expected to be a threat to the harbor and no historical data to support either was found.

#### D. Summary

##### 1. Area Impact

The Seoul/Inchon area has suffered primarily from flooding as a result of tropical cyclone passage. The storm of 19 August 1972 is typical of the major tropical cyclones that have had severe impact upon the area. On 19 August 1972 a recorded 18 inches of rain fell on Seoul and its environs in five hours. The Han River, which flows through the center of

Seoul, overflowed having risen from a normal depth of 4 1/2 ft to a crest of 36 1/2 ft (Ref. 3). Massive landslides caused loss of houses and many deaths; more than 650 people lost their lives and 326,000 were left homeless.

2. Incheon Harbor

Incheon Harbor with its coastal location, has better facility for handling heavy flooding and has suffered less than inland areas. The normal tidal range at Incheon Harbor and the occurrence of non-tropical cyclone caused tidal deviations of the same order of magnitude as the surge earlier discussed places storm surge threat in the range of normal yearly tidal deviation.

3. Evaluation

Incheon Harbor does not appear to be seriously threatened by storm surge. Tropical cyclones have normally lost much of their strength before reaching the Incheon area. This fact, combined with a low tropical cyclone threat frequency and the extreme tidal changes which occur at Incheon all serve to lessen the storm surge threat to the harbor area.

## Pusan/Chinhae<sup>1</sup>

### B. Physical Characteristics of Site

#### 1. Geographic Location (Figure I-1)

Pusan (35°06'N, 129°02'E) and Chinhae (35°08'N, 128°41'E) are located on the south-east coast of the Korean Peninsula. Pusan Harbor, South Korea's principal deepwater port, is bordered on the north by the Nakdong River Basin and on the south by the Korea Strait as is Chinhae Harbor. The Japanese islands of Honshu and Kyushu are about 120 mi south across the Korean Strait.

#### 2. Physical Description - Topography and Bathymetry (Figures P-1 and P-2)

The ports of Pusan and Chinhae are located along an extremely broken and irregular coastline. The south coast, described geologically as a submerged coastline, features a maze of more than 2000 islands and numerous small basins. Offshore the basins contain deep water and create an intricate coastline of extensive, highly irregular peninsulas enclosing irregularly shaped bays.

To the north the Nakdong River Basin is the major geological feature. The Nakdong River enters the sea via a large delta immediately west of the city of Pusan.

---

<sup>1</sup>Due to close proximity (<20 n mi apart) these two sites will be treated together.

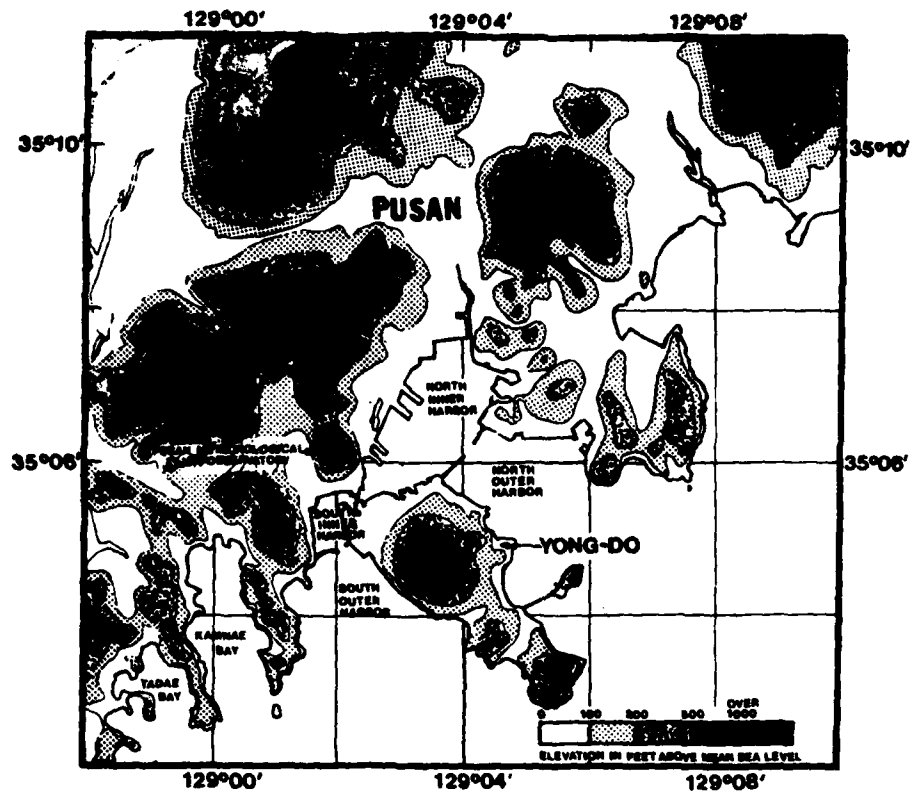


Figure P-1.  
Topography map for Pusan Harbor (from Ref. 5).

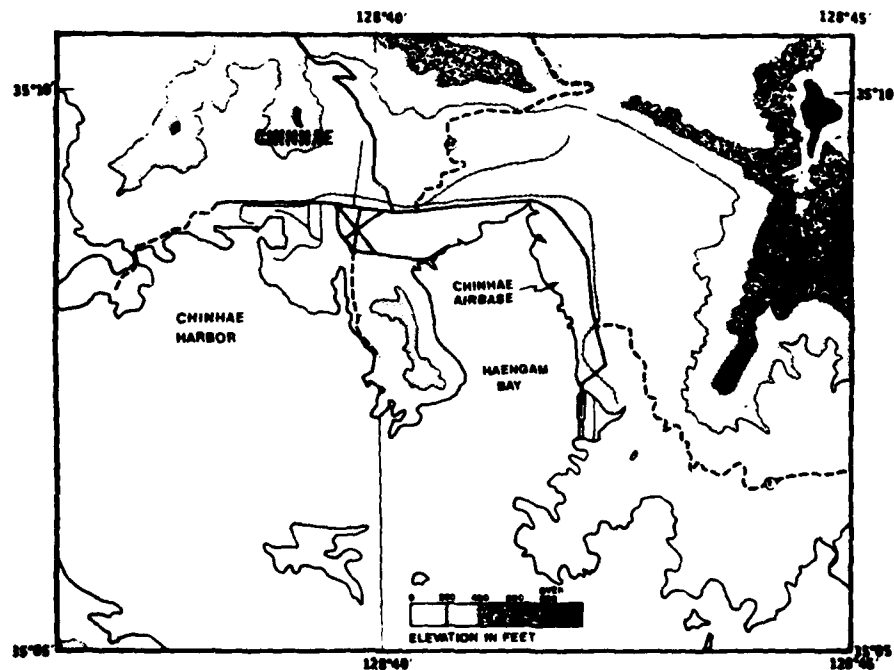


Figure P-2.  
Topography map for Chinhae Harbor (from Ref. 5).

Pusan Harbor is divided into a northern and southern harbor by Yong-Do Island. The harbor is well protected by hills ranging to over 1000 ft in all quadrants except the south and southeast. In the southeast the North Inner Harbor opens to the North Outer Harbor via a breakwater with an 1150 ft opening width and approximately 40 ft depth (LLW). Depths in the inner harbor range 20-50 ft while outer harbor depths range to 60 ft. The South Harbor opens to the south via a breakwater (800 ft width, 18-20 ft depth). South Harbor is used primarily by Korean coastal vessels.

Chinhae Harbor (Fig. P-2) is also well protected by surrounding hills on all sides except to the south and southeast where broken passage to the sea is formed through several offshore islands. The steep slope of the surrounding hills and heights of over 1000 ft in several places act as effective wind barriers. Numerous islands of the same character serve to break any organized swell and wave patterns from the open sea to the south in their approach to the harbor. Depths in Chinhae Harbor range 15-45 ft with basin depths between the outside islands reaching over 100 ft.

### 3. Locations of Structural Development

Pusan Harbor, a deep water port, is South Korea's principal commercial port. The U.S. Navy's Military Sealift Command utilizes one pier (Pier 8) within the North Inner Harbor.

South Korea, embarked upon commercial maritime expansion, has an extensive and ongoing construction program at Pusan. With excellent protection for its inner harbor (previously discussed) plans are underway to construct a second breakwater across the mouth of the North Outer Harbor allowing port expansion into that area via reclaimed land. Current structural development is limited to the inner harbor (note Fig. P-1). Average seawall height in the inner harbor is 9-10 ft above LLW.

Chinhae Harbor (Fig. P-2) serves as the Republic of Korea's (ROK) principal naval base. (The town of Chinhae is also the home of the ROK Naval Academy.) Most of the present buildings and naval facilities were constructed by the Japanese prior to WWII. Present U.S. facilities are limited to a site of approximately 84 acres on the ROK Naval Base.

### C. Storm Surge

#### 1. Tropical Cyclone Frequency and Characteristics

In a study (Ref. e) which considered Pusan and Chinhae jointly, 55 tropical cyclones threatened Pusan/Chinhae during a 26 year period (1948-1973). (A midpoint between the two harbors was used to describe the 180 n mi radius.) The NCC Tropical Cyclone Tape (Ref.6) was analyzed separately for Pusan and Chinhae over a period of 35 years (1945-79). Threat tropical cyclones totaled 43 for both

Pusan and Chinhae for passage within 180 n mi radius of each. Thus each site is threatened by 1-2 tropical cyclones annually.

Tropical cyclones reaching South Korea ( $35^{\circ}\text{N}$ ) have usually started to degrade as a storm system. They have generally recurved and although their forward speed of movement may be greater than average, general weakening of the storm system reduces the threat of typhoon force winds and associated storm surge. In a 35-year period (1945-1979), 17 storms of typhoon strength ( $\geq 64$  kt winds) were found a threat to Pusan and 15 for Chinhae (Ref.6).

An analysis of wind observations (Ref.e) over a 26 year period (1948-73) determined that less than one third (29%) of the tropical cyclones that threatened Pusan produced gale force ( $\geq 34$  kt) winds at the meteorological observatory atop a 150 ft hill near the harbor. Of the tropical cyclones producing gale force winds 62% passed to the west of Pusan causing southerly winds from the unprotected quadrant. The maximum sustained wind during the analysis period was 70 kt in September 1959 caused by the passage of Typhoon Sarah 10 n mi west of Pusan.

A similar analysis at Chinhae over a shorter 11-year period (1951-61) determined that less than one quarter (24%) of the tropical cyclones that threatened Chinhae produced gale

force ( $\geq 34$  kt) winds at the harbor. Typhoon Sarah produced sustained winds from the northeast of 90 kt, recorded at nearby Chinhae Air Base, and 55 kt recorded in Chinhae. (Hills just northeast of Chinhae which reach over 600 ft acted to decrease the velocity of the wind.)

For both Pusan and Chinhae the most dangerous path for a typhoon to follow would be one just west (of each site) at a distance equal to the radius of maximum wind of the storm (approximately 25-50 n mi). This would bring winds from the strong semicircle of the storm into the site from a southerly direction (least protected by topography) and also create the greatest potential for storm surge. Typhoons approaching Pusan and Chinhae do so primarily from the SE to SW quadrant (about 80% for both).

## 2. Characteristics of Storm Surge

Due to the generally weakened condition of the storm system at south Korean latitudes and the few storms which approximate the most dangerous path described above, storm surge has not historically been a frequent occurrence at Pusan or Chinhae (Refs. d, e, f, g, h and j). The characteristic height for the majority of the tropical cyclone storm surge affecting the two areas has been within the same magnitude of other meteorological disturbances. Reference d listed tropical cyclones as the cause

of maximum tidal deviation at Chinhae in only 2 of 12 years (1959-70). (Pusan did not have data available for 1959-64.)

However, the potential for serious storm surge at Pusan and Chinhae does exist as demonstrated by Typhoon Sarah (17 September 1959). Sarah passed across the South Korean Coast between Pusan and Chinhae and apparently caused severe surge in the Pusan area. Tidal gauge information for Pusan was not available but Chinhae suffered a 3.6 ft surge. Sarah was at 935 mb central pressure while approximately 100 n mi SSW of Pusan. Both Pusan and Chinhae are enclosed embayments open to the SSW, therefore most vulnerable to a tropical cyclone on a path of recurvature moving to the NE as Sarah. Reference a gives a 4.9 ft surge height for a 50-year storm for Pusan. Typhoon Sarah was the worst typhoon to hit the Korean Peninsula in 50 years (Ref. b). Maximum wind wave heights with typhoon strength winds ( $\geq 64$  kt) are 4-5 ft for the inner harbor at Pusan and 12-15 ft for the outer harbor with a 100 n mi southerly fetch. In Chinhae Harbor a northerly wind of typhoon strength would cause only 3 ft waves whereas one of such strength from the south would cause 8-10 ft waves (Ref. e).

Seiches are a common phenomenon in Pusan Harbor but are small in amplitude and resonance is highly unlikely (Ref.a). The mean

tidal range of 2.8 ft and spring range of 4.0 ft. The mean tide level at Chinhae is 3.7 ft with 4.8 ft and 6.6 ft ranges for mean and spring tides, respectively.

#### D. Summary

##### 1. Area/Harbor Impact

The southern coast of Korea, as does other areas of Korea, suffers primarily from storm associated flooding during the passage of tropical cyclones. However, when the storm is of greater strength than normal and strikes in the monsoon rain season as did Sarah the damage can be extensive. The combination of heavy typhoon rains adding to already swollen riverbeds and the concurrent storm surge left 669 persons dead and over \$100 million in damage. The Pusan area was hardest hit with more than 15,000 homes washed away, damaged or destroyed by floods and storm surge. Military installations in the Pusan and Taegu areas suffered \$900,000 damage and damage to Pusan port exceeding \$100,000 (Ref.b).

Typhoon Judy (26 August 1979) caused 115 deaths in southern Korea and over \$40 million damage (flooding was the primary cause) after recurving from the Shanghai area and skirting the southern Korean coast. Judy carried estimated winds of only 40 kt while 250 n mi SSW of Pusan (Ref.3).

## 2. Evaluation

Pusan and Chinhae are normally threatened by tropical cyclones which have started to degrade as a storm system. Their locations at the southern tip of Korea increases the threat somewhat due to the over water approach available to the tropical cyclones through the Korea Strait. This is somewhat mitigated by the breakwater at Pusan and the offshore islands at Chinhae. Both are susceptible to a combined threat of flooding and storm surge as evidenced by the damage associated with the passage of Typhoon Sarah.

#### IV. ANALYSIS AND CONCLUSIONS

##### 1. Comments on Survey

A survey was conducted for nine western Pacific sites. The survey was to examine the susceptibility of each site to storm surge events and further to determine: what historical records are available; what water levels are critical at each site; what personal interviews would reveal concerning past events and what topographical and bathymetric charts were available.

A pre-visit review of literature to determine storm surge events of consequence at the nine sites met with little success. Two facts emerged in the review. First, most storm surge research and documentation was of a general nature (not site specific). Second, that research or documentation found on specific sites were for those areas where storm surge was either more frequent, better documented or a greater threat to the populace. The National Climatic Center Tropical Cyclone Tape (Ref. 6) on the western Pacific and Indian Ocean proved the greatest single source of tropical cyclone information. The Typhoon Havens Handbook for the Western Pacific and Indian Oceans along with the JTWC Annual Typhoon Reports, the Mariners Weather Log, the OFDA Disaster History List and others provided additional information on specific storms.

A visit to DMA in Washington prior to the western Pacific site visits determined that on-going exchange agreements with the foreign governments involved provides the U.S. Navy with the latest and most accurate topography

and bathymetry charts for the individual sites. This subject was not pursued at the sites due to the sensitivity of the information.

The availability of historical records at each site seemed to vary directly with the frequency and intensity of past tropical cyclone events at each site. (Buckner Bay an exception!) Guam's past events were best documented while Diego Garcia had little data. However, even Apra Harbor data was marred by the loss of the tidal recorder during the two largest storms of recent history. The same proved true at Pusan during the landfall of typhoon Sarah (note site writeups). In many cases the best data available from local sources could only indicate that "high water" occurred with the specific tropical cyclone. Tidal gauges were not installed at five of the sites with the four remaining sites providing some data for storms of record. In some cases local analysis of past events or published articles provided storm surge information.

Newspapers were a poor source of accurate data. Articles reviewed primarily dealt with the effects of the tropical cyclone and human interest stories. Wind levels were reported in some cases but water levels from storm surge or storm tide were not given except in very general terms - i.e., over a certain road or seawall. Safety and prudent action require that a threatened populace leave a low-lying area which is subject to inundation by high storm tides. This, in effect, leaves no observers to record actual water levels during the storm.

Interviews with naval personnel and local residents at each site did provide information on some recent tropical cyclones to strike respective sites. Useful comments are noted in specific site writeups. Generally, attempts to determine vulnerability of specific sites to high water levels resolved into two areas of naval concern; the preparation (or departure) of afloat vessels and the possible damage to fixed structures at low elevations. Advice to afloat vessels is given amply in Reference 5. A general knowledge of past storm surge history (at least recent history) at the site is the usual basis for preparation upon the approach of a tropical cyclone, but the degree of concern and preparation is usually dictated by the size and intensity of the approaching cyclone. Of all sites visited, only at Apra Harbor on Guam did navy personnel seem to exhibit high "tropical cyclone awareness". (Possibly due to a combination of major strikes there in recent history and the presence of the typhoon warning center (JTWC) for the western Pacific area).

Some general conclusions reached by the investigator after many interviews were:

- o Storm surge is not generally perceived to be a threat at the sites (Guam an exception).
- o Site specific storm surge information and guidance is lacking.
- o Many knowledgeable naval personnel were interested in storm surge but some question the value of a forecast due to the large errors associated with tropical cyclone forecasting.
- o Sites with infrequent or weak threats had the least knowledge and interest levels.
- o Some interest was expressed in a maximum storm surge level determination (historical or theoretical).

The determination of acceptable critical water levels at the nine sites was not possible in this survey due to several reasons. First, "critical" was difficult to define in a standardized way for nine sites whose U.S. assets varied from zero (Inchon) to millions of dollars. (Do critical levels include host country assets?) Second, it would be a sizeable task to evaluate each of the site plant accounts for replacement values of those buildings which were located at or below a specified level of elevation. (Some of the sites were reluctant to disclose such information.) Third, high water levels from storm surge (or storm tide) may cause a level of damage, down-time and inconvenience, yet not be considered critical to one command, whereas it may be considered critical to another at the same elevation and exposure. Individual site evaluations do discuss structural placement and elevations. Determination of historical high water levels at each site was a difficult problem due to the limited amount and accuracy of data available.

What is presently known of storm surge in complex geophysical areas suggest that the best data would be obtainable only through an accurate inundation model of the individual site. Evaluation of storm surge levels at the sites (see writeups) provides limited value guidance due to the short historical periods of record, the complex geophysical configuration for many of the sites, and the lack of a "worst case" tropical cyclone to give a good indication of potential storm surge.

In an attempt to provide additional data, engineering studies on the harbors or ports were obtained where possible. These studies contain, as a part of the engineering analysis; a meteorological and oceanographic section which

describes a 50-year (or 100-year) storm as a worse case engineering hazard. However, multiple studies for one site sometimes provided different characteristics for the same hazard, probably indicating a weak statistical data base as analysis methodologies were similar. Significant wave data and information on tsunamis and seiching in the harbors was included in the studies where available.

## 2. Analysis of Site and Storm Characteristics.

Any attempt to do a definitive analysis on storm surge threat at any of the sites would require a substantial amount of historical data. The U.S. Army Corps of Engineers (COE), in attempting to make a similar assessment along U.S. Gulf and Atlantic Coasts where substantially more data is available, stated (pg.3, Ref.8):

"Abnormally high winds, pounding waves, and storm surge from hurricanes produce severe damage and a threat to life. The COE is responsible for assessing the potential for damage resulting from hurricanes along coasts, proposing and designing structures to alleviate this damage, and consulting with State and local communities on these matters. Local records of hurricane behavior are inadequate for these purposes, not only because of often incomplete water-level observations but also these and other records may be available for only a few years. In addition, hurricanes may cross a particular section of coast infrequently. Communities that have been spared a severe storm for decades or may never have experienced a severe hurricane in recorded history are not immune to this danger in the future."

The comments are pertinent to this study.

However, in an attempt to provide a level of information above that which can be discerned from the site survey data, some simple analyses were performed upon the NCC Tropical Cyclone Tape data (Ref.6). Simpson and Riehl (Ref.1) demonstrated a simple method to compute return periods for dangerous hurricanes which would occur on an average, only once every 50 or 100 years. Applying these methods to data extracted from the NCC tape a series of points were determined, plotted and curve fitted. From the resultant curve for each site a 100-year storm was determined in terms of maximum winds (Figs. A-1 through A-9).

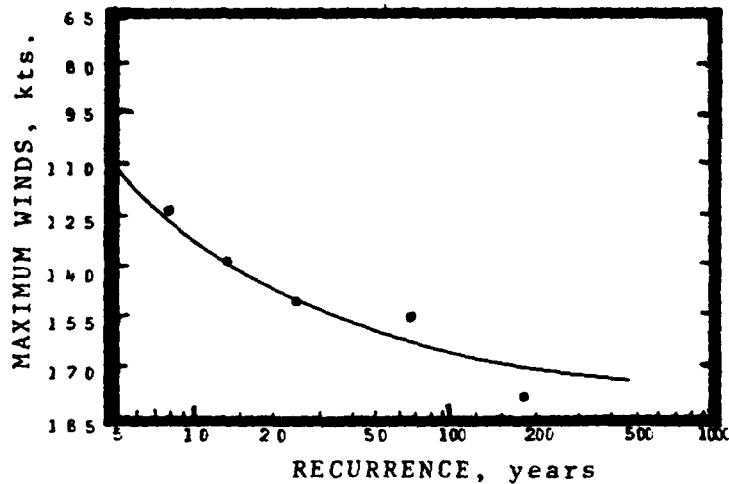
Caution is advised in use due to limited data and the fact that the 100-year storm is calculated for the 180<sup>1</sup> n mi threat radius surrounding the site therefore the storm may not necessarily be within the radius of strongest winds nor on the worst path or at the worst position. Terrain or other local effects are not considered. Octant of approach information is also provided for each site.

Due to the critical path requirement which is necessary for a tropical cyclone to generate a maximum or near maximum surge at a particular site and the low probability of such a track, it is generally felt that typhoon intensity and recurrence data are the most reliable guides to determine storm surge threat over a period of time. Frequency of both tropical cyclone threat (within 180 n mi radius) and typhoon threat (within 60 n mi radius) as well as an average speed of approach were determined for each site. This data and that previously discussed is presented in a table (Table A-1) so that the sites may be compared somewhat quantitatively<sup>2</sup> for potential storm surge threat. The complex geophysical terrain of many of the sites and the lack of substantial recorded data for the site itself makes any other comparison methodology very problematic.

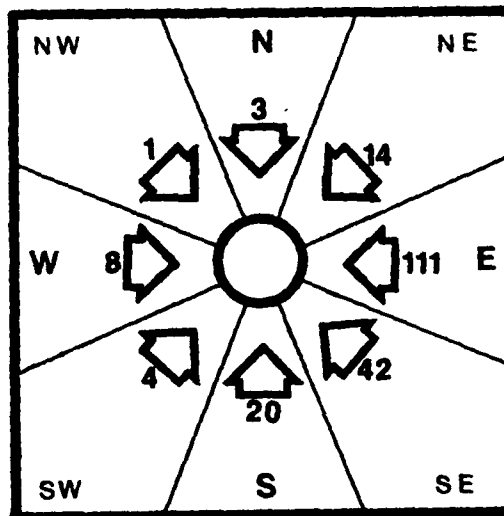
---

<sup>1</sup> Due to the limited 35-year data base this author felt that a 180 n mi threat radius rather than a 60 n mi threat radius would be a more representative sector of the population of tropical cyclones passing each site. Ideally, with a large data base, 60 n mi would be more representative of the maximum storm surge threat as it would be much closer to the radius of maximum winds therefore would represent maximum surge threat.

<sup>2</sup>A note of caution - as was pointed out in the opening paragraph of this section, sufficient data to perform a statistically reliable storm surge analysis is generally not available. The analysis is presented to be used for relative comparisons of site threat.

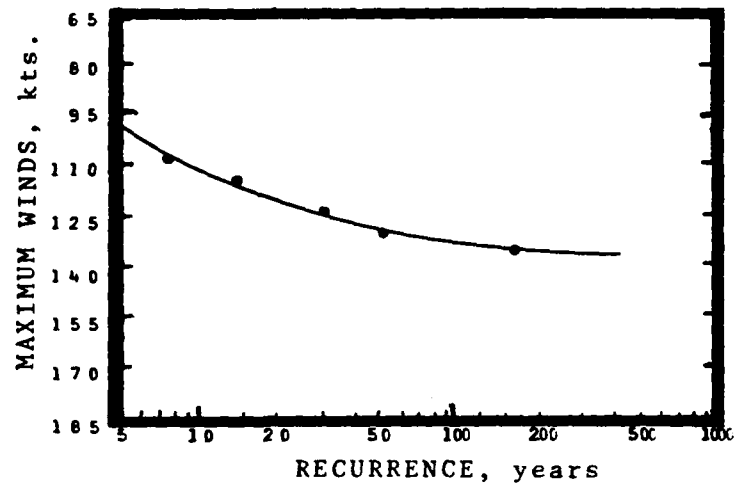


Based on data from 127 tropical cyclones over 35 years (1945-1979).

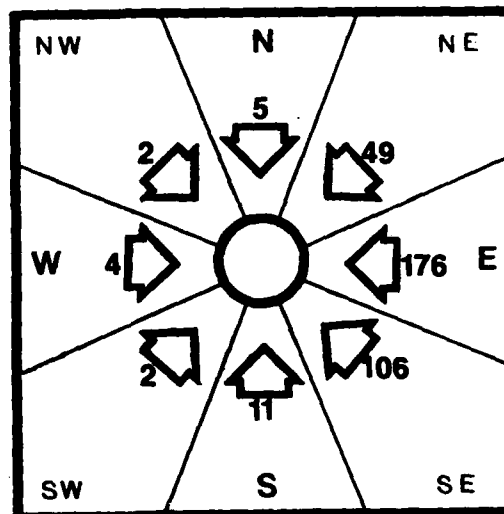


Octant of tropical cyclone approach, 76 years (1904-1979) data.

Figure A-1  
Apra Harbor, Guam. Return periods for typhoon coming within 180 n mi (above) and octant for tropical cyclone approach (below).

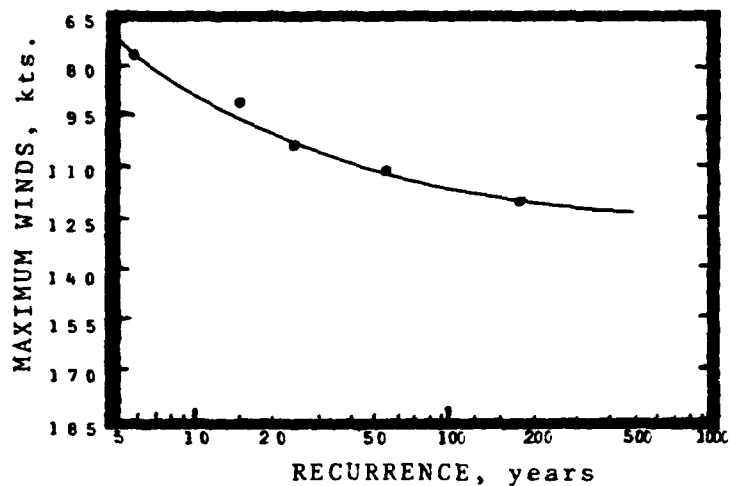


Based on data from 160 tropical cyclones over 35 years (1945-1979).

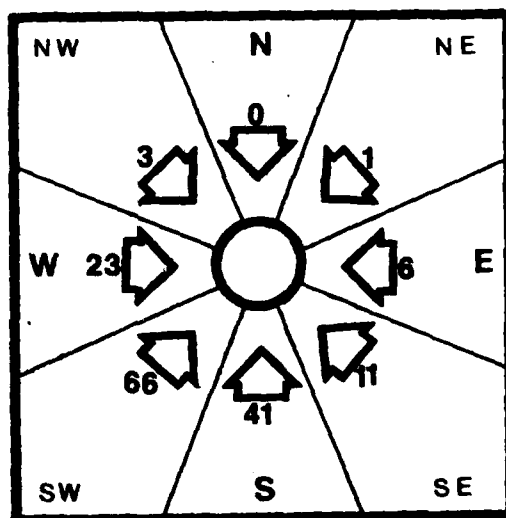


Octant of tropical cyclone approach, 96 years (1884-1979) data.

Figure A-2  
Subic Bay, Philippines. Return periods for typhoons coming within 180 n mi (above) and octant for tropical cyclone approach (below).

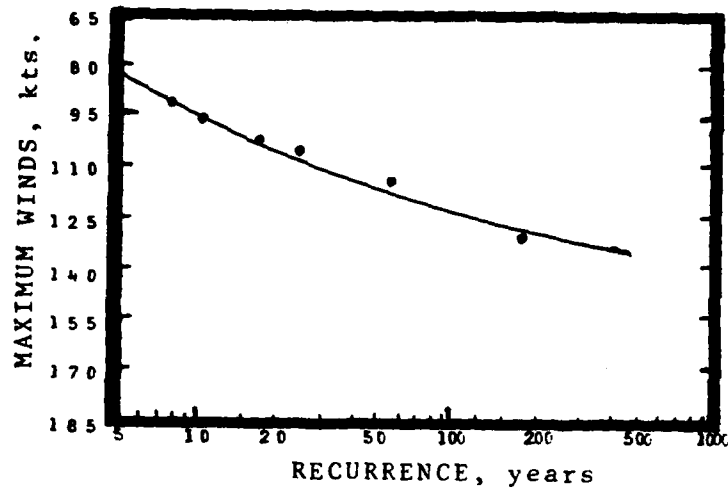


Based on data from 92 tropical cyclones over 35 years (1945-1979).

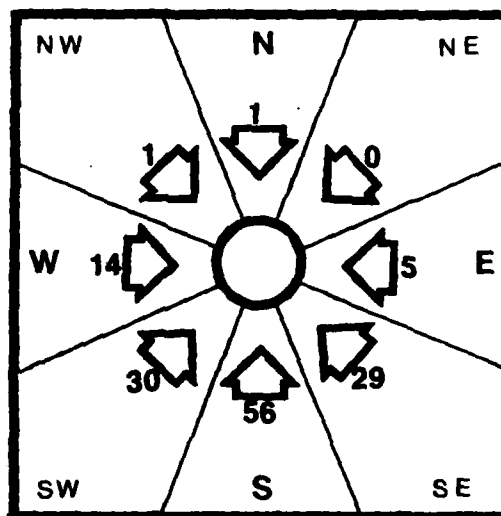


Octant of tropical cyclone approach, 69 years (1911-1979) data.

Figure A-3  
Yokosuka Harbor, Japan. Return periods for typhoons coming within 180 n mi (above) and octant for tropical cyclone approach (below).

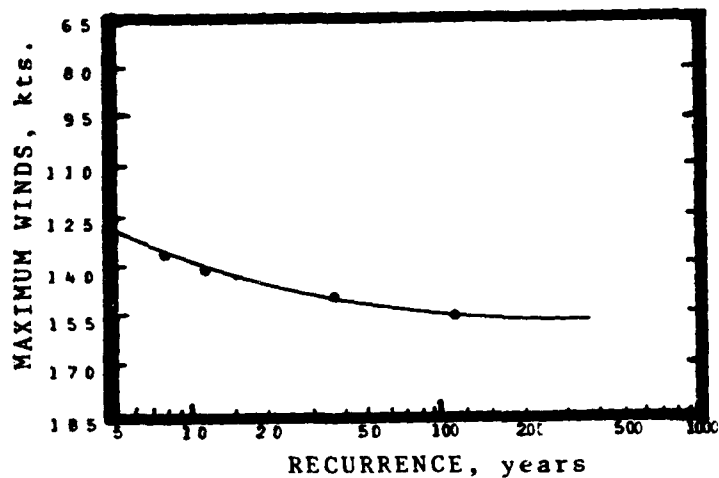


Based on data from 91 tropical cyclones over 35 years (1945-1979).

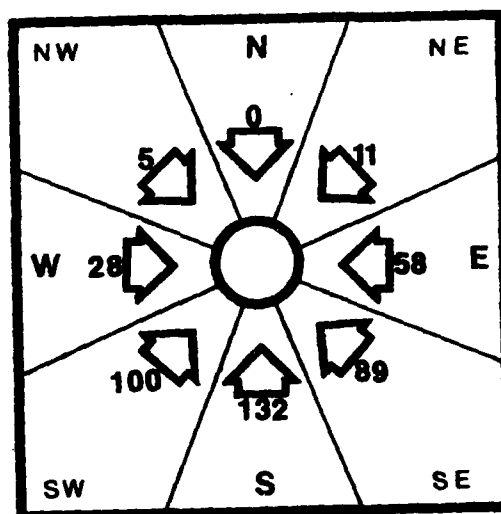


Octant of tropical cyclone approach, 69 years (1911-1979) data.

Figure A-4  
Sasebo Harbor, Japan. Return periods for typhoons coming within 180 n mi (above) and octant for tropical cyclone approach (below).

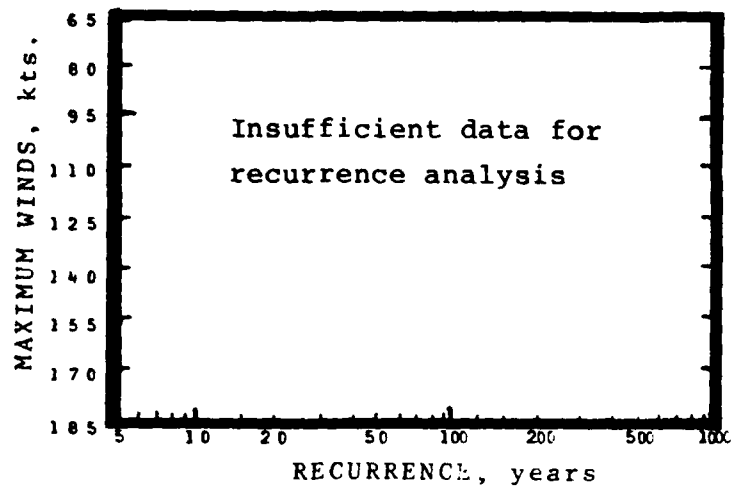


Based on data from 143 tropical cyclones over 35 years (1945-1979).

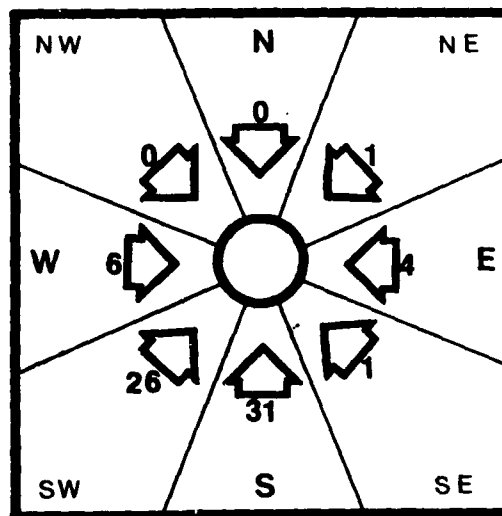


Octant of tropical cyclone approach, 96 years (1884-1979) data.

Figure A-5  
Buckner Bay. Return periods for typhoons coming within 180 n mi (above) and octant for tropical cyclone approach (below).

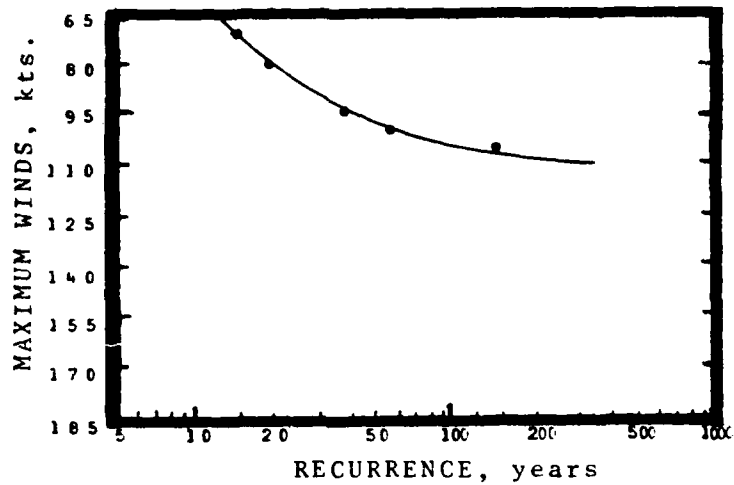


Based on data from 33 tropical cyclones over 35 years (1945-1979).

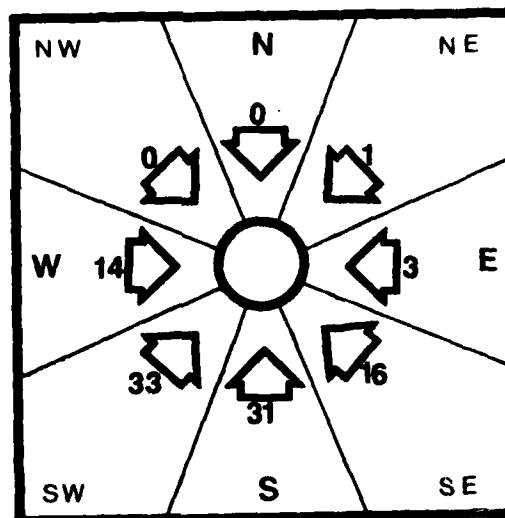


Octant of tropical cyclone approach, 69 years (1911-1979) data.

Figure A-6  
Inchon Harbor, Korea. Return periods for typhoons coming within 180 n mi (above) and octant for tropical cyclone approach (below).

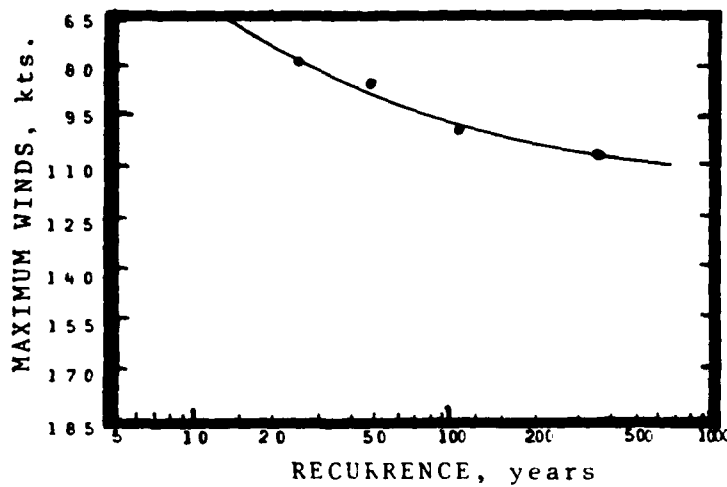


Based on data from 43 tropical cyclones over 35 years (1945-1979).

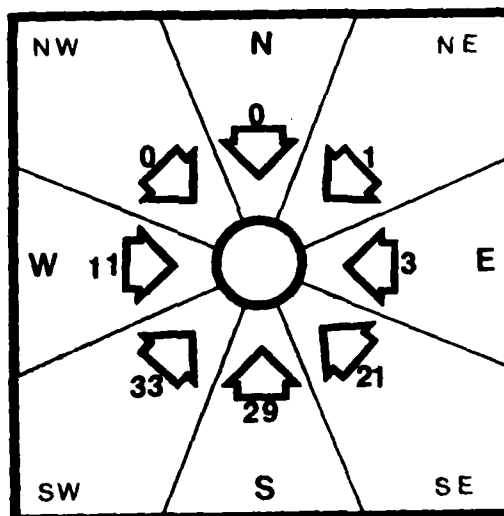


Octant of tropical cyclone approach, 69 years (1911-1979) data.

Figure A-7  
Pusan Harbor, Korea. Return periods for typhoons coming within 180 n mi (above) and octant for tropical cyclone approach (below).

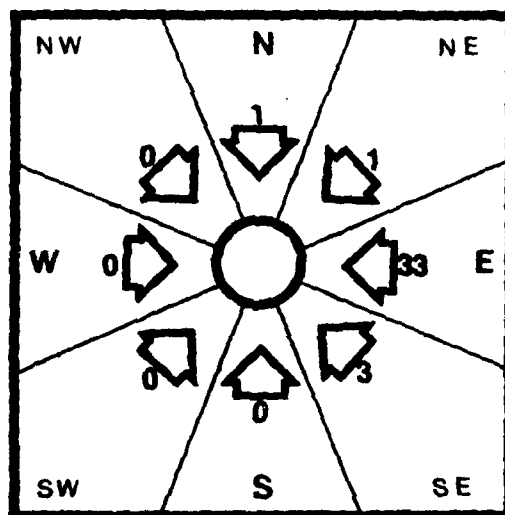
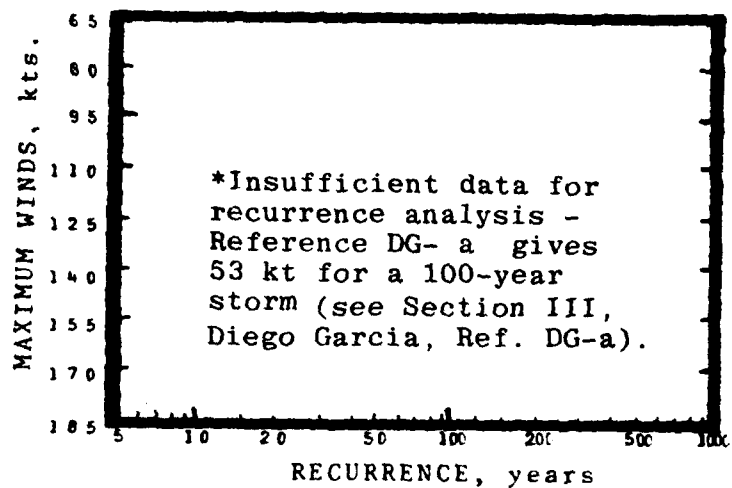


Based on data from 43 tropical cyclones over 35 years (1945-1979).



Octant of tropical cyclone approach, 69 years (1911-1979) data.

Figure A-8  
Chinhae Harbor, Korea. Return periods for typhoons coming within 180 n mi (above) and octant for tropical cyclone approach (below).



Octant of tropical cyclone approach, 53 years (1927-1979) data.

Figure A-9  
Diego Garcia. Return periods for typhoons coming within 180 n mi (above) and octant for tropical cyclone approach (below).

TABLE A-1

Tropical Cyclone/Typhoon Characteristics for Navy Sites of Interest (based on 35 years [1945-1979])

|                       | Tropical Cyclone<br>Threat Frequency<br>(180 n mi radius)<br>(no/yr) | Typhoon ( $\geq 64$ kt)<br>Threat Frequency <sup>4</sup><br>(60 n mi radius)<br>(no/yr) | 100 year<br>Typhoon<br>(Max Wind in<br>(kts)<br>(180 n mi rad) | Avg Forward<br>Speed for<br>Typhoons (kt)<br>(180 n mi rad) | Saffir-Simpson <sup>1</sup><br>Potential Surge <sup>1</sup><br>(ft) |
|-----------------------|--|---|--|---|---|
| Apra Harbor           | 3.6  | 0.4   | 165  | 11.7  | >18   |
| Subic Bay             | 4.6  | 0.7   | 135  | 11.1  | 13-18   |
| Yokosuka<br>Harbor    | 2.6  | 0.4   | 119  | 21.3  | 13-18   |
| Sasebo<br>Harbor      | 2.6  | 0.3   | 124  | 20.5  | 13-18   |
| Buckner<br>Bay        | 4.1  | 0.9   | 151  | 10.2  | >18   |
| Inchon<br>Harbor      | 0.9  | 0.01  | xx <sup>2</sup>  | 19.2  | 4-5   |
| Pusan<br>Harbor       | 1.2  | 0.1   | 105  | 15.4  | 9-12  |
| Chinhae<br>Harbor     | 1.2  | 0.1   | 99   | 15.3  | 9-12  |
| Diego Garcia<br>Atoll | 0.7  | xx <sup>2</sup>   | (53) <sup>3</sup>  | xx <sup>2</sup>   | $\leq 4$  |

<sup>1</sup>Saffir-Simpson potential storm surge for storm indicated in 100 year storm column. Scale developed for Atlantic Hurricanes.

<sup>2</sup>Insufficient data.

<sup>3</sup>Insufficient data - 53 kts from source DG-a (see Section III. Diego Garcia, Ref. a).

<sup>4</sup>60 n mi radius frequency is an estimate obtained by taking one-third of typhoons in 180 n mi radius.

The site survey data provides only a qualitative feel for the threat problem due to the inability to gather data from similar sources for all sites, the variable periods over which the data had been collected and the different levels of reliability attached to the data. However, the survey data generally supports the analyzed data.

Apra Harbor (Guam) is subject to the most intense 100 year typhoon threat while three of the nine sites are subject to storms (within the threat radius) with winds  $\geq 135$  kt, which places them in the catastrophic damage zone on the Saffir-Simpson scale of hurricane intensity. However, both Subic Bay and Buckner Bay appear to have better geophysical protection<sup>3</sup> with respect to dominant tropical cyclone paths than does Guam. Site reports indicate extensively more damage caused in Apra Harbor even though both Subic Bay and Buckner Bay have a higher typhoon strike frequency. Yokosuka and Sasebo with less intense 100-year typhoons and less frequent threat also seem to be well protected from large potential surge by site location relative to normal storm passage or by local topography and bathymetry.

Pusan is subject to storm surge but also to less intense and less frequent typhoons. Pusan also has plans to install a second breakwater which should further diminish storm effects in the inner harbor. Chinhae is better protected from storm effects than is Pusan, although subject to essentially the same tropical cyclones.

---

<sup>3</sup>Note - A more complete discussion is found in the individual site reports for these and following comments.

### 3. Conclusions

The conclusions of this survey evolve from the following:

- A literature search through the best known sources for data on storms of record at the nine western Pacific and Indian Ocean sites;
- A review of the general literature on storm surge threat evaluation;
- A visit to NOAA and NHC modelers to discuss results of storm surge inundation and barrier modeling results;
- On-site survey visits to eight of the nine sites to identify and gather data and interview people concerning past storm surge events;
- Evaluation of the tropical cyclone parameters for recorded storms which pose a threat to each site.

Recognizing the basic weaknesses of the survey as a method to determine tropical cyclone storm surge threat, it is believed nonetheless that sufficient data has been gained and analyzed to draw the following conclusions:

1) Demonstrated past damage and frequency of strike at Apra Harbor combined with the extensive U.S. Navy facilities located at vulnerable levels in the harbor area indicate that the site should receive first priority for any future U.S. Navy storm surge study or work.

2) The combined threat of storm intensity and high threat frequency place both Subic Bay and Buckner Bay high on the suspect list but with local geophysical features seeming to mitigate storm effects. Normal tropical cyclone paths over the mountainous terrain of Luzon reduces storm intensity at Subic Bay. However, the possibility exists for

a storm to approach the harbor from the southeast around to the southwest thereby retaining greater strength and posing greater surge threat to Subic Bay. Buckner Bay is much more difficult to assess. All indications are that storm surge should be a substantial threat with only the barrier reefs and islands to mitigate the threat to the bay. However, very little evidence was found to support past storm surge events. Subic Bay with large naval assets at low levels and potential threat should receive higher priority. Buckner Bay should be further analyzed if navy assets (below 10-12 ft MSL) at White Beach justify the costs.

3) Yokosuka, Sasebo, Pusan and Chinhae fall into a medium threat range (relative to other sites) for threat frequency and intensity. Of these, Yokosuka has greater U.S. Naval assets but also seems to be the least threatened of the four due to its location, geophysical relief and normal tropical cyclone tracks. Pusan Harbor, being directly open to the south-southeast, is most vulnerable to direct storm effects.

4) Inchon and Diego Garcia fall into a low threat category primarily due to the low frequency and less than typhoon strength winds for a 100-year threat typhoon. Note specific site reports for a detailed discussion of potential threats.

#### GENERAL REFERENCES

1. Simpson, R.H. and H. Riehl, 1981: The Hurricane and its Impact, Louisiana State University Press, 398 pp.
2. Jelesnianski, C.P., 1972: SPLASH (Special Program to List Amplitudes of Surges from Hurricanes): I. Landfall Storms, NOAA Tech. Memo II NWSTDL-46.
3. Office of Foreign Disaster Assistance, Disaster History List (updated 10/29/81) and Special Reports.
4. Chin, P.C., 1972: Tropical Cyclone Climatology for the China Seas and Western Pacific from 1884 to 1970; Royal Observatory Hong Kong, 207 pp.
5. Brand, S. and J.W. Belloch, 1976: Typhoon Havens Handbook for the Western Pacific and Indian Oceans, NAVENVPREDRSCHFAC Technical Paper 5-76.
6. NOAA National Climatic Center Tropical Cyclone Deck 933. (Tape No. 9636).
7. Brand, S., R.P. Chambers, H.J.C. Woo, J.E. Cermak, J.J. Lou and M. Danard, 1979: A Preliminary Analysis of Mesoscale Effects of Topography on Tropical Cyclone-Associated Coastal Surface Winds, NEPRF TR 79-03.
8. Schwerdt, R.W.; F.P. Ho, and R.P. Watkins, 1979: Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Windfields, Gulf and East Coasts of the United States, NOAA Technical Report NWS-23, 343 pp.
9. U.S. Army Coastal Engineering Research Center, 1977: Shore Protection Manual; Vol. I, II, III; Dept. of the Army CoE.
10. Crutcher, H.L. and R.G. Quayle, 1974: Mariners Worldwide Climatic Guide to Tropical Storms at Sea, NAVAIR 50-1C-061, 312 pp.
11. Naval Oceanography Command Center/Joint Typhoon Warning Center Annual Typhoon Reports. (Years 1961-1981)
12. Hydrology Committee - 1980, U.S. Water Resources Council, 1980: An Assessment of Storm Surge Modeling.

13. Personal discussions with National Hurricane Center modeling group - especially Mr. Brian Jarvinen, Dec. 1981.
14. World Meteorological Organization (WMO) Publication No. 500, 1978: Present Techniques of Tropical Storm Surge Prediction.
15. World Meteorological Organization (WMO) Bulletins - Significant Weather in 19xx.
16. Mariners Weather Logs, NOAA.
17. Jelesnianski, C.P., 1980: Tropical Storm Surge Forecasting in the National Weather Service, TDL, NOAA.
18. Nickerson, J.W., 1971: Storm Surge Forecasting, NAVWEARSCHFAC Technical Paper No. 10-71.

## APPENDIX A

One method for displaying storm surge model output is presented in the following example for Tampa Bay, Florida. This information was developed for the Tampa Bay regional council using a particular storm surge model with simulated hurricanes which typify those likely to threaten Tampa. This material was extracted for this report from Gilmore (1982)<sup>1</sup>.

Developed by the National Oceanic and Atmospheric Administration's (NOAA) National Weather Service, the model is called SLOSH and estimates the Sea, Lake, and Overland Surges from Hurricanes (Jelesnianski and Chen, 1979<sup>2</sup> and Tampa Bay Regional Planning Council, 1981<sup>3</sup>). Tampa Bay values were computed for 3600 grid points on a "telescoping" polar grid system. The level of resolution varies from one grid square representing approximately 1.6 square miles on the coast to 0.6 square miles inland. Several storm tracks were evaluated, comprising 4 directions of travel with 3 to 8 parallel tracks for each direction. Five storm intensities were used, each corresponding to a category on the "Saffir/Simpson Scale," which was developed by Herbert Saffir and Dr. Robert H. Simpson. Table 1 outlines the Saffir/Simpson scale.

<sup>1</sup>Gilmore, Richard D., 1982: "An Evaluation of Tampa, Florida as a Hurricane Haven", ODSI Preliminary contract report to the Naval Environmental Prediction Research Facility.

<sup>2</sup>Jelesnianski, C.P. and J. Chen, 1979: SLOSH (Sea, Lake, and Overland Surges from Hurricanes). National Oceanic and Atmospheric Administration, Technical Development Lab, in preparation.

<sup>3</sup>Tampa Bay Regional Planning Council, 1981: Hurricane Evacuation Plan, Tampa Bay Region, Florida. Technical Data Report, U.S. Army Corps of Engineers, Jacksonville, FL.

TABLE 1  
Saffir/Simpson Scale

| <u>SCALE<br/>NUMBER</u> | <u>CENTRAL PRESSURE</u> |               | <u>WIND</u> |              | <u>DAMAGE</u> |
|-------------------------|-------------------------|---------------|-------------|--------------|---------------|
|                         | <u>MILLIBARS</u>        | <u>INCHES</u> | <u>MPH</u>  | <u>KNOTS</u> |               |
| 1                       | > 980                   | > 28.94       | 74-95       | 64-83        | Minimal       |
| 2                       | 965-979                 | 28.50-28.91   | 96-110      | 84-95        | Moderate      |
| 3                       | 945-964                 | 27.91-28.47   | 111-130     | 96-113       | Extensive     |
| 4                       | 920-944                 | 27.17-27.88   | 131-155     | 114-135      | Extreme       |
| 5                       | < 920                   | < 27.17       | 155+        | 135+         | Catastrophic  |

TABLE 7

SLOSH Surge Height Calculations for  
Selected Locations in Tampa Bay.  
All heights are feet above MSL.1

|                    |                                | LOCATION <sup>3</sup> |      |      |      |      |      |      |      |     |      |      |
|--------------------|--------------------------------|-----------------------|------|------|------|------|------|------|------|-----|------|------|
| TRACK <sup>2</sup> | SAFFIR/SIMPSON<br>SCALE NUMBER | 1                     | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9   | 10   | 11   |
| LNN                | 1                              | 3.5                   | 2.4  | 4.3  | 3.5  | 5.2  | 4.8  | 3.8  | 3.2  | 3.3 | 3.0  | 4.1  |
|                    | 3                              | 6.5                   | 7.8  | 8.3  | 9.7  | 10.4 | 8.9  | 6.9  | 6.0  | 6.0 | 5.8  | 7.5  |
|                    | 5                              | 6.3                   | 10.0 | 8.1  | 9.4  | 10.2 | 8.7  | 6.7  | 5.7  | 5.7 | 5.5  | 7.3  |
| LNP                | 1                              | 4.0                   | 3.1  | 4.9  | 5.7  | 6.2  | 5.5  | 4.3  | 3.6  | 3.6 | 3.4  | 4.7  |
|                    | 3                              | 7.7                   | 8.9  | 9.7  | 11.7 | 12.5 | 10.8 | 8.3  | 7.0  | 7.0 | 6.9  | 9.1  |
|                    | 5                              | 7.4                   | 10.9 | 9.7  | 11.2 | 12.1 | 10.4 | 7.9  | 6.9  | 6.8 | 6.7  | 8.7  |
| LTN                | 1                              | 4.3                   | 4.1  | 5.5  | 6.6  | 7.2  | 6.4  | 4.8  | 3.8  | 3.9 | 3.7  | 5.2  |
|                    | 3                              | 8.7                   | 9.5  | 11.0 | 13.8 | 15.1 | 13.0 | 9.4  | 8.1  | 7.7 | 7.8  | 10.3 |
|                    | 5                              | 9.9                   | 11.7 | 13.0 | 15.7 | 17.0 | 14.5 | 10.5 | 8.9  | 8.5 | 8.6  | 11.5 |
| LCL                | 1                              | 4.6                   | 4.7  | 5.8  | 7.2  | 8.1  | 7.2  | 5.2  | 3.9  | 3.8 | 3.6  | 5.6  |
|                    | 3                              | 9.8                   | 9.7  | 11.9 | 16.2 | 17.8 | 15.2 | 10.7 | 8.9  | 8.0 | 8.4  | 11.8 |
|                    | 5                              | 11.4                  | 13.2 | 15.1 | 18.7 | 21.0 | 17.5 | 12.2 | 9.9  | 8.8 | 9.8  | 13.4 |
| LTC                | 1                              | 4.6                   | 2.3  | 5.5  | 7.1  | 8.1  | 7.3  | 5.3  | 3.9  | 3.5 | 3.4  | 5.7  |
|                    | 3                              | 10.2                  | 9.3  | 11.6 | 16.7 | 18.7 | 16.4 | 11.1 | 9.3  | 7.2 | 8.4  | 12.4 |
|                    | 5                              | 13.3                  | 12.1 | 16.0 | 22.8 | 25.7 | 22.6 | 14.9 | 11.4 | 8.4 | 10.8 | 16.6 |
| LST                | 1                              | 4.0                   | 1.0  | 4.5  | 5.8  | 6.7  | 6.7  | 4.8  | 3.6  | 3.3 | 3.1  | 5.1  |
|                    | 3                              | 8.2                   | 7.0  | 8.8  | 13.8 | 15.7 | 14.8 | 9.8  | 8.7  | 6.4 | 7.2  | 10.7 |
|                    | 5                              | 12.8                  | 11.1 | 14.3 | 22.2 | 25.2 | 23.4 | 14.2 | 11.6 | 7.9 | 9.9  | 15.8 |
| LKE                | 1                              | 2.4                   | 1.0  | 2.4  | 1.9  | 4.2  | 4.4  | 3.2  | 2.8  | 2.2 | 2.1  | 3.3  |
|                    | 3                              | 4.3                   | 1.0  | 4.2  | 7.3  | 8.2  | 8.6  | 6.3  | 6.0  | 3.5 | 3.9  | 6.2  |
|                    | 5                              | 4.8                   | 1.0  | 3.5  | 7.5  | 9.7  | 10.2 | 8.8  | 9.9  | 3.7 | 5.4  | 7.1  |
| LTS                | 1                              | 1.3                   | 1.0  | 1.0  | 1.0  | 1.9  | 2.4  | 2.0  | 1.9  | 1.5 | 1.5  | 1.7  |
|                    | 3                              | 1.5                   | 1.0  | 1.1  | 1.0  | 3.5  | 3.9  | 3.0  | 3.2  | 2.3 | 1.9  | 2.4  |
|                    | 5                              | 1.6                   | 1.0  | 1.0  | 1.0  | 2.4  | 3.2  | 2.8  | 4.9  | 2.7 | 2.4  | 1.7  |

TABLE 2 (continued)

| TRACK <sup>2</sup> | SAFFIR/SIMPSON<br>SCALE NUMBER | LOCATION <sup>3</sup> |     |     |      |     |     |     |     |     |     |     |
|--------------------|--------------------------------|-----------------------|-----|-----|------|-----|-----|-----|-----|-----|-----|-----|
|                    |                                | 1                     | 2   | 3   | 4    | 5   | 6   | 7   | 8   | 9   | 10  | 11  |
| N30                | 3                              | 5.0                   | 5.8 | 5.5 | 6.7  | 6.7 | 6.0 | 4.9 | 4.5 | 5.0 | 4.6 | 5.3 |
| N15                | 3                              | 5.6                   | 7.8 | 6.9 | 9.0  | 9.1 | 7.9 | 5.5 | 5.4 | 6.0 | 5.4 | 6.3 |
| N00                | 3                              | 5.1                   | 6.6 | 6.4 | 9.3  | 9.6 | 8.1 | 5.3 | 4.7 | 5.1 | 4.4 | 6.1 |
| P30                | 3                              | 3.6                   | 1.5 | 4.0 | 2.7  | 4.8 | 4.3 | 3.5 | 3.1 | 3.5 | 3.2 | 3.8 |
| P15                | 3                              | 4.1                   | 3.9 | 4.9 | 6.0  | 6.4 | 5.5 | 4.1 | 3.6 | 4.7 | 3.9 | 4.6 |
| P00                | 3                              | 4.4                   | 5.2 | 5.4 | 8.5  | 8.1 | 6.6 | 4.5 | 4.1 | 4.5 | 4.4 | 5.1 |
| ET                 | 3                              | 4.4                   | 5.1 | 4.9 | 10.1 | 9.7 | 6.5 | 3.9 | 3.6 | 2.9 | 3.5 | 4.4 |
| EN                 | 3                              | 5.5                   | 7.7 | 6.3 | 11.3 | 9.4 | 6.5 | 4.8 | 4.5 | 3.9 | 4.3 | 5.3 |
| EC                 | 3                              | 3.8                   | 3.0 | 4.3 | 2.3  | 4.5 | 4.0 | 3.1 | 4.0 | 3.2 | 3.2 | 3.7 |
| ES                 | 3                              | 1.3                   | 1.0 | 1.0 | 1.0  | 1.4 | 1.4 | 1.2 | 1.4 | 1.9 | 1.5 | 1.2 |

1. SLOSH values are estimated to be within plus or minus 15 percent of observed water levels. Values do not consider wave set-up, rainfall, or astronomical tidal effects (Tampa Bay Regional Planning Council, 1981.)
2. Track codes are keyed to Figure 1.
3. Location numbers correspond to locations listed below and are keyed to Figure 2.
  1. Port of St. Petersburg
  2. Safety Harbor (Upper Old Tampa Bay)
  3. Port Tampa
  4. Upper Hillsborough Bay
  5. McKay Bay
  6. Alafia River
  7. Little Manatee River
  8. Port Manatee
  - 9-11. Anchorages

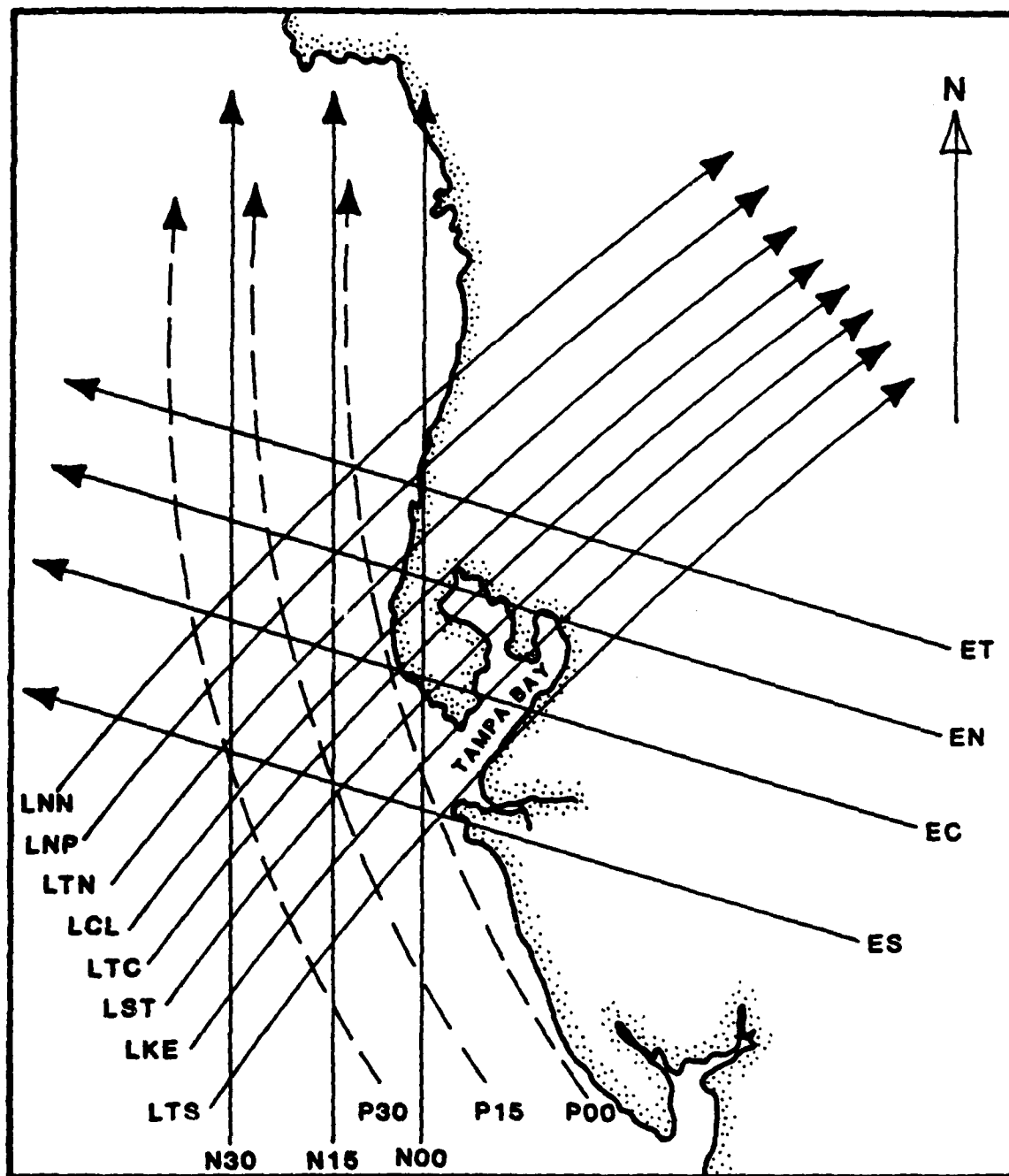


FIGURE 1: Selected tracks of hurricanes simulated by SLOSH numerical storm surge model for Tampa Bay (Tampa Bay Regional Planning Council, 1981).

Data printouts for several computer runs of the SLOSH model were reviewed, and surge height calculations for 11 selected points in Tampa Bay were extracted for 18 storm tracks. These values are given in Table 2. Saffer/Simpson categories 1,3 and 5 are given where available, otherwise only category 3 is given. Figure 1 depicts specific storm tracks used for the SLOSH model calculations while Figure 2 shows each of the selected locations for which data was extracted.

A review of the values given in Table 2 reveals that the surge heights for locations in the upper reaches of Tampa Bay, especially in the main port area in Hillsborough Bay, are significantly higher than those near the mouth of the bay. The highest water levels would result from category 5 storms moving inland just north of the main portion of Tampa Bay - tracks IST, LTC and LCL.

Water levels resulting from what is essentially a "worst case" storm (such as a category 5 storm following track "LTC"), would inundate all of the Interbay Peninsula (Figure 2), Davis Islands, Seddon Island, Hookers Point and the land area around greater Tampa Bay to a distance of as such as 4 miles inland in some areas.

Also of significance is the effect that westward tracking storms such as "ET" or "EN" would have on water levels. In both cases, a category 3 storm would cause water rises of near 10 feet in Hillsborough Bay, which would inundate Davis Islands, Seddon Island, Hookers Point and about 50 percent of the Interbay Peninsula, including most of MacDill AFB.

Astronomical tides in Tampa Bay are semi-diurnal with a range of about 2.3 feet. According to U.S. Coast Pilot 5, 1980<sup>4</sup> published by the U.S. Department of Commerce, "A strong offshore wind sometimes lowers the water surface at Tampa and in the dredged channels as much as 4 feet, and retards the time of high water by as much as 3 hours. A continued SW wind raises the water by nearly the same amount and advances the time of high water by as much as 1 hour."

Tidal currents of 3 knots or more at the strength of the greater ebb of the day may occur in Egmont Channel, Passage Key Inlet, and off Port Tampa, but flood velocities seldom exceed 2 knots. The tidal currents are greatly affected by winds. A clockwise rotary tidal current is observed 6.7 miles west of Egmont Key Light, and has considerable daily inequality (U.S. Department of Commerce, 1980).

---

<sup>4</sup>U.S. Department of Commerce, 1980: United States Coast Pilot 5, Atlantic Coast: Gulf of Mexico, Puerto Rico, and Virgin Islands. National Oceanic and Atmospheric Administration, National Ocean Survey, Washington, DC.

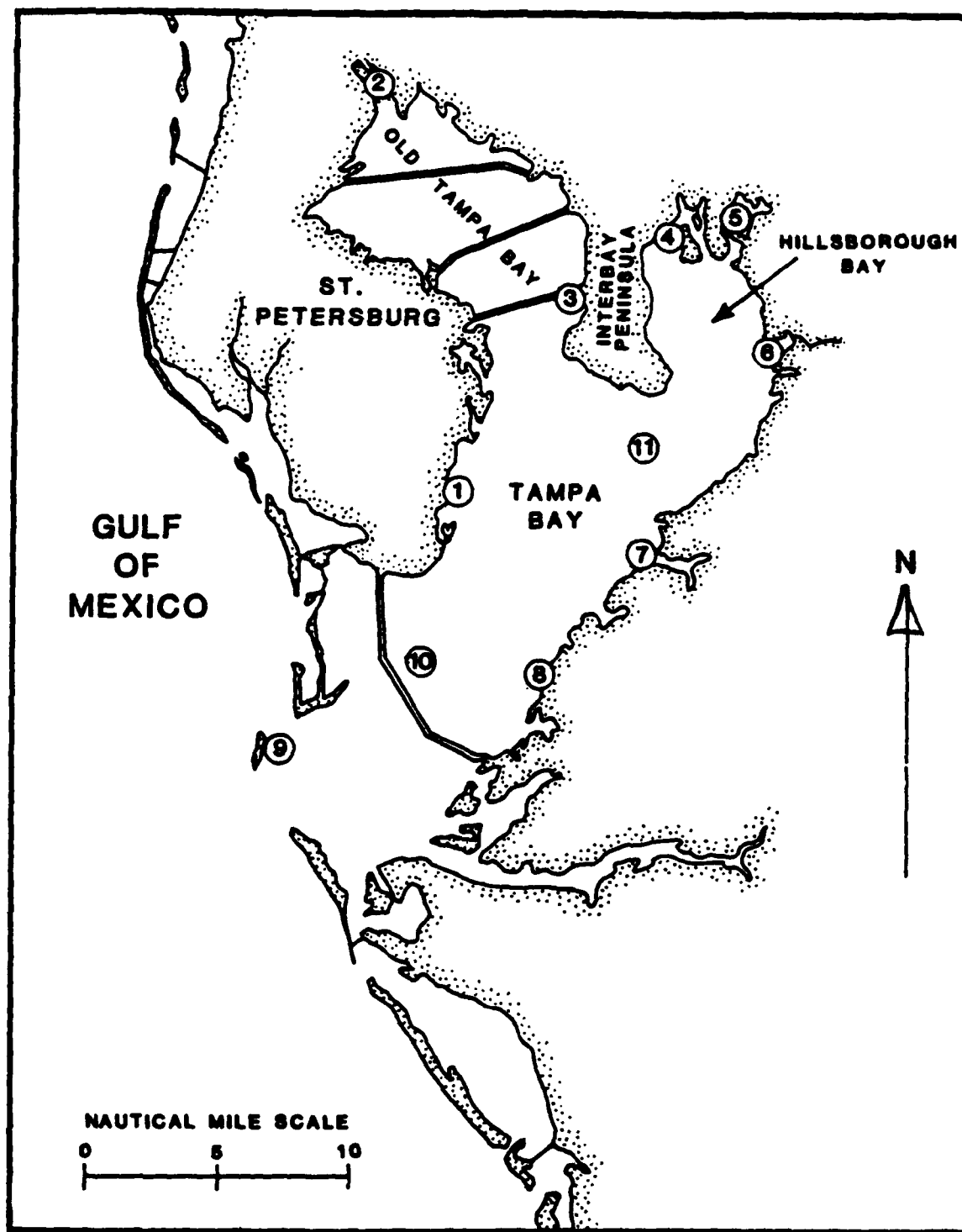


FIGURE 2: SLOSH numerical storm surge locations as listed in Table 2.

DISTRIBUTION: CR 83-02

COMMANDER IN CHIEF  
U.S. PACIFIC FLEET, CODE 02M  
PEARL HARBOR, HI 96860

COMTHIRDFLT  
CODE N33  
PEARL HARBOR, HI 96860

COMSEVENTHFLT  
ATTN: FLT METEOROLOGIST, N30W  
FPO SAN FRANCISCO 96601

COMTHIRDFLT  
ATTN: NSAP SCIENCE ADVISOR  
CODE N702/OIT  
PEARL HARBOR, HI 96860

COMSEVENTHFLT  
ATTN: NSAP SCIENCE ADVISOR  
BOX 167  
FPO SEATTLE 98762

COMMANDER  
U.S. NAVAL FORCES, JAPAN  
FPO SEATTLE 98762

COMMANDER  
U.S. NAVAL FORCES, MARIANAS  
FPO SAN FRANCISCO 96630

COMMANDER  
U.S. NAVAL FORCES, PHILIPPINES  
BOX 30/N3  
FPO SAN FRANCISCO 96651

COMMANDER  
U.S. NAVAL FORCES, KOREA  
APO SAN FRANCISCO 96301

COMMANDER  
AMPHIBIOUS GROUP 1  
ATTN: METEOROLOGICAL OFFICER  
FPO SAN FRANCISCO 96601

COMMANDING OFFICER  
USS NIMITZ (CVN-68)  
ATTN: MET. OFFICER, OA DIV.  
FPO NEW YORK 09542

COMMANDING OFFICER  
USS CONSTELLATION (CV-64)  
ATTN: MET. OFFICER, OA DIV.  
FPO SAN FRANCISCO 96635

COMMANDING OFFICER  
USS CORAL SEA (CV-43)  
ATTN: MET. OFFICER, OA DIV.  
FPO SAN FRANCISCO 96632

COMMANDING OFFICER  
USS ENTERPRISE (CVN-65)  
ATTN: MET. OFFICER, OA DIV.  
FPO SAN FRANCISCO 96636

COMMANDING OFFICER  
USS KITTY HAWK (CV-63)  
ATTN: MET. OFFICER, OA DIV.  
FPO SAN FRANCISCO 96634

COMMANDING OFFICER  
USS MIDWAY (CV-41)  
ATTN: MET. OFFICER, OA DIV.  
FPO SAN FRANCISCO 96631

COMMANDING OFFICER  
USS RANGER (CV-61)  
ATTN: MET. OFFICER, OA DIV.  
FPO SAN FRANCISCO 96633

COMMANDING OFFICER  
USS CARL VINSON (CVN-70)  
ATTN: MET. OFFICER, OA DIV.  
FPO NEW YORK 96629

COMMANDING OFFICER  
USS BLUERIDGE (LCC-19)  
ATTN: MET. OFFICER  
FPO SAN FRANCISCO 96628

COMMANDING OFFICER  
USS NEW ORLEANS (LPH-11)  
ATTN: MET. OFFICER  
FPO SAN FRANCISCO 96627

COMMANDING OFFICER  
USS OKINAWA (LPH-3)  
ATTN: MET. OFFICER  
FPO SAN FRANCISCO 96625

COMMANDING OFFICER  
USS TRIPOLI (LPH-10)  
ATTN: METEOROLOGICAL OFFICER  
FPO SAN FRANCISCO 96626

COMMANDING OFFICER  
USS TARAWA (LHA-1)  
FPO SAN FRANCISCO 96622

COMMANDING OFFICER  
USS BELLEAU WOOD (LHA-3)  
ATTN: METEOROLOGICAL OFFICER  
FPO SAN FRANCISCO 96623

COMMANDING OFFICER  
USS PELELIU (LHA-5)  
FPO SAN FRANCISCO 96624

COMMANDING OFFICER  
USS POINT LOMA (AGDS-2)  
ATTN: METEOROLOGICAL OFFICER  
FPO SAN FRANCISCO 96677

CINCPAC  
BOX 13  
STAFF CINCPAC J37  
CAMP SMITH, HI 96861

SPECIAL ASST. TO THE ASST.  
SECRETARY OF THE NAVY (R&D)  
ROOM 4E741, THE PENTAGON  
WASHINGTON, DC 20350

CHIEF OF NAVAL RESEARCH (2)  
LIBRARY SERVICES, CODE 734  
RM 633, BALLSTON TOWER #1  
800 QUINCY ST.  
ARLINGTON, VA 22217

CHIEF OF NAVAL OPERATIONS  
(OP-952)  
U.S. NAVAL OBSERVATORY  
WASHINGTON, DC 20390

CHIEF OF NAVAL OPERATIONS  
NAVY DEPT. OP-986G  
WASHINGTON, DC 20350

CHIEF OF NAVAL OPERATIONS  
U.S. NAVAL OBSERVATORY  
DR. R. W. JAMES, OP-952D1  
34TH & MASS. AVE., NW  
WASHINGTON, DC 20390

CHIEF, ENV. SVCS. DIV.  
OJCS (J-33)  
RM. 2877K, THE PENTAGON  
WASHINGTON, DC 20301

NAVAL DEPUTY TO THE  
ADMINISTRATOR, NOAA  
ROOM 200, PAGE BLDG. #1  
3300 WHITEHAVEN ST. NW  
WASHINGTON, DC 20235

OFFICER IN CHARGE  
NAVOCEANCOMDET  
BOX 81  
U.S. NAVAL AIR STATION  
FPO SAN FRANCISCO 96637

OFFICER IN CHARGE  
NAVOCEANCOMDET  
U.S. NAVAL AIR FACILITY  
FPO SEATTLE 98767

OFFICER IN CHARGE  
NAVOCEANCOMDET  
MONTEREY, CA 93940

OFFICER IN CHARGE  
U.S. NAVOCEANCOMDET  
APO SAN FRANCISCO 96519

OFFICER IN CHARGE  
U.S. NAVOCEANCOMDET  
FPO SAN FRANCISCO 96685

OFFICER IN CHARGE  
U.S. NAVOCEANCOMDET  
FLEET ACTIVITIES  
FPO SEATTLE 98770

OFFICE OF NAVAL RESEARCH  
EAST/CENTRAL REGIONAL OFFICE  
BLDG. 114, SECT. D  
459 SUMMER ST.  
BOSTON, MA 02210

COMMANDING OFFICER  
NORDA, NSTL STATION  
BAY ST. LOUIS, MS 39529

COMNAVOCEANCOM  
NSTL STATION  
BAY ST. LOUIS, MS 39529

COMNAVOCEANCOM  
ATTN: J. W. OWNBEY, CODE  
N542 NSTL STATION  
BAY ST. LOUIS, MS 39529

COMMANDING OFFICER  
NAVOCEANO LIBRARY  
NSTL STATION  
BAY ST. LOUIS, MS 39522

COMMANDING OFFICER  
FLENUMOCEANCEN  
MONTEREY, CA 93940

COMMANDING OFFICER  
NAVWESTOCEANCEN  
BOX 113  
PEARL HARBOR, HI 96860

COMMANDING OFFICER  
U.S. NAVOCEANCOMCEN  
BOX 12, COMNAVMIANAS  
FPO SAN FRANCISCO 96630

COMMANDING OFFICER  
U.S. NAVOCEANCOMFAC  
FPO SEATTLE 98762

COMMANDING OFFICER  
U.S. NAVOCEANCOMFAC  
BOX 63, NAS (CUBI PT)  
FPO SAN FRANCISCO 96654

SUPERINTENDENT  
LIBRARY REPORTS  
U.S. NAVAL ACADEMY  
ANNAPOLIS, MD 21402

CHAIRMAN  
OCEANOGRAPHY DEPT.  
U.S. NAVAL ACADEMY  
ANNAPOLIS, MD 21402

PRESIDENT  
NAVAL WAR COLLEGE  
ATTN: GEOPHYSICS OFFICER  
NEWPORT, RI 02840

COMMANDER (2)  
NAVAIRSYSCOM  
ATTN: LIBRARY (AIR-0004)  
WASHINGTON, DC 20361

COMMANDER  
NAVAIRSYSCOM (AIR-333)  
WASHINGTON, DC 20361

COMMANDER  
NAVAIRSYSCOM  
MET. SYS. DIV. (AIR-553)  
WASHINGTON, DC 20360

NAVAL POSTGRADUATE SCHOOL  
METEOROLOGY DEPT.  
MONTEREY, CA 93940

NAVAL POSTGRADUATE SCHOOL  
OCEANOGRAPHY DEPT.  
MONTEREY, CA 93940

COMMANDING OFFICER  
WEATHER SERVICE OFFICE  
U.S. MCAS (HELICOPTER)  
FPO SEATTLE 98772

USAFETAC/TS  
SCOTT AFB, IL 62225

OFFICER IN CHARGE  
SERVICE SCHOOL COMMAND  
DET. CHANUTE/STOP 62  
CHANUTE AFB, IL 61868

HQ 1ST WEATHER WING/DN  
HICKAM AFB, HI 96853

DET 4 HQ AWS/CC  
APO SAN FRANCISCO 96334

DET 5 1WW/CC  
APO SAN FRANCISCO 96274

DET. 8, 1WW/CC  
APO SAN FRANCISCO 96239

DET 18, 30 WS  
APO SAN FRANCISCO 96301

DIRECTOR (12)  
DEFENSE TECH. INFORMATION  
CENTER, CAMERON STATION  
ALEXANDRIA, VA 22314

FEDERAL COORD. FOR METEORO.  
SERVS. & SUP. RSCH. (OFCM)  
11426 ROCKVILLE PIKE  
SUITE 300  
ROCKVILLE, MD 20852

CHIEF, SCIENTIFIC SERVICES  
NWS, PACIFIC REGION  
P.O. BOX 50027  
HONOLULU, HI 96850

DIRECTOR, CENTRAL PACIFIC  
HURRICANE CENTER NWS, NOAA  
HONOLULU, HI 96819

HEAD, ATMOS. SCIENCES DIV.  
NATIONAL SCIENCE FOUNDATION  
1800 G STREET, NW  
WASHINGTON, DC 20550

MR. W. G. SCHRAMM/WWW  
WORLD METEOROLOGICAL  
ORGANIZATION  
CASE POSTALE #5, CH-1211  
GENEVA, SWITZERLAND

DIRECTOR, JTWC  
BOX 17  
FPO SAN FRANCISCO 96630

DIRECTOR, ROYAL OBSERVATORY  
NATHAN ROAD, KOWLOON  
HONG KONG, B.C.C.

MARITIME METEOROLOGY DIV.  
JAPAN METEOROLOGICAL AGENCY  
OTE-MACHI 1-3-4 CHIYODA-KU  
TOKYO, JAPAN

LIBRARY  
METEOROLOGICAL RSCH INST.  
1-1, NAGAMINE, YATABE-MACHI  
TSUKUBA-GUN  
IBARAKI-KEN 305 JAPAN

JAPAN METEOROLOGICAL AGENCY  
3-4 OTEMACHI 1-CHOME,  
CHIYODA-KU  
TOKYO 100, JAPAN

CHAIRMAN  
EARTH SCIENCE DEPT.  
KONG JU NATIONAL TEACHERS  
COLLEGE  
KONG JU, KOREA

KOREA OCEAN RESEARCH &  
DEVELOPMENT INSTITUTE  
P.O. BOX 17, YANG JOE  
SEOUL, KOREA

DEPT. OF METEOROLOGY  
COLLEGE OF ARTS & SCIENCES  
UNIVERSITY OF THE PHILIPPINES  
DILMAN, QUEZON CITY 3004  
PHILIPPINES

DIRECTOR, TYPHOON MODERATION  
RSCH & DEVEL. OFFICE, PAGASA  
MINISTRY OF NATIONAL DEFENSE  
1424 QUEZON AVE.  
QUEZON CITY, PHILIPPINES

NATIONAL WEATHER SERVICE  
PHILIPPINE ATMOS. GEOPHYS. &  
ASTRO. SERV. ADMIN (PAGASA)  
1424 QUEZON AVE.  
QUEZON CITY, PHILIPPINES

TECHNICAL LIBRARY  
WEATHER BUREAU  
NATIONAL DEFENSE DEPT.  
LUNGSOD NG QUEZON  
QUEZON, PHILIPPINES

DR. D. LEE HARRIS  
COLLEGE OF ENGINEERING  
336 WEIL HALL  
UNIV. OF FLORIDA  
GAINESVILLE, FL 32611

